DOT/FAA/AR-95/86

Office of Aviation Reserach
Washington, D.C. 20591

Proceedings of the FAA-NASA Sixth International Conference on the Continued Airworthiness of Aircraft Structures

Atlantic City, New Jersey
June 27-28, 1995

December 1995

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/AR-95/86	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FAA-NASA SIXTH INTERNATIONAL CONFERENCE ON THE CONTINUED AIRWORTHINESS OF AIRCRAFT STRUCTURES		5. Report Date December 1995
		6. Performing Organization Code DOT/FAA/AR-95/86
7. Author(s) Compiled by: Catherine A. Bigelow		8. Performing Organization Report No.
9. Performing Organization Name and Address Joint Publication by: Airport and Aircraft Safety Research and Development Division FAA Technical Center Atlantic City International Airport, NJ 08405	NASA Langley Research Center Materials Division Hampton, VA 23681	10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, D.C. 20591		13. Type of Report and Period Covered Proceedings June 27-28, 1995
		14. Sponsoring Agency Code AAR-430

15. Supplementary Notes

Edited by Catherine A. Bigelow, FAA Technical Center, Atlantic City International Airport, NJ

16. Abstract

This publication contains the proceedings of the FAA-NASA Sixth International Conference on the Continued Airworthiness of Aircraft Structures. These conferences are held to disseminate information on the status of activities in transport and commuter aircraft certification, rulemaking, and airline maintenance related issues for both new and aging aircraft and to offer a forum for participation by all interested parties. The theme of the conference this year was the accomplishments of the past six years and how the successes can continue.

17. Key Words Widespread Fatigue Damage (WFD), Nondestructive Inspection (NDI), Maintenance, repair, structural integrity, Aging aircraft	18. Distribution Statement This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	240	

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EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) jointly sponsored the Sixth International Conference on the Continued Airworthiness of Aircraft Structures held June 27-28, 1995, in Atlantic City, New Jersey.

The conference was the sixth such conference in a continuing series held in alternate years and jointly sponsored by the FAA and NASA. These conferences are held to disseminate information on the status of activities in transport and commuter aircraft certification, rulemaking, and airline maintenance related issues for both new and aging aircraft and to offer a forum for participation by all interested parties. The theme of the conference this year was the accomplishments of the past six years and how the successes can continue.

Full-length manuscripts were requested from the authors of papers presented; these paper are included in the proceedings.

The members of the Conference Organizing Committee are as follows:

Chris C. Seher, Conference Chairman, FAA Technical Center
Charles E. Harris, Conference Co-Chairman, NASA Langley Research Center
Jack F. McGuire, Boeing Commercial Airplane Group
Amos W. Hoggard, Douglas Aircraft Company
John W. Lincoln, ASC/ENFS, US Air Force
John Bristow, CAA, UK
David Lotterer, Air Transport Association
William Keil, Regional Airline Association
Daniel Salvano, Federal Aviation Administration

Many thanks are due to the Organizing Committee for their valuable assistance. Their help was instrumental in setting the agenda and acting as the Session Chairmen.

Approximately 240 people attended the conference. The affiliations of the attendees included 25% from government agencies, 13% from academia, and 44% from industry.

Chris C. Seher
FAA Technical Center

Welcoming Remarks
(Video Address)
Honorable Frank Lautenberg (R-New Jersey)

Hello, I'm Senator Frank Lautenberg. Welcome to New Jersey. I would like to thank you for giving me this opportunity today, and I am sorry that I cannot be there in person. Firstly, I want to commend all of you for the attention that you are giving to the airworthiness of our aircraft. Despite the incredible number of movements that take place each and every day throughout the world, and the great safety record, it is appropriate that we continue to examine it. I don't think any of us can shut out the image of the scattered remains of Pan Am 103 or of the sight of the Aloha flight sitting on the runway with its fuselage peeled away like a tin can. As the former Chairman of the Transportation Appropriations Committee and a member of the President's Aviation Security and Terrorism Commission, I have been deeply involved with aviation safety issues and I still carry with me those images. I have worked hard to enhance safety in the air. Last year the Subcommittee allocated $3 million more than the Administration's request to continue work in the Aging Aircraft area. It provided the full amount requested for airport security and restored cuts which were made by the House, cuts which would have terminated research on airport and aircraft security. It also restored one million dollars to continue the development of ice detector systems, anti-icing materials, and research on airplane stalling. And finally in Committee, I restored 4.6 million dollars that the House cut in aircraft systems fire safety.

I have also been a strong supporter of the FAA Center for Excellence. It's the first of its kind aimed at conducting research on crashes and aircraft structures. This award-winning facility was established here in New Jersey in 1992 to respond to safety issues related to aging aircraft. The Aloha flight made it clear that long term research in conjunction with FAA inspections will help us better understand the impact of aging on our aircraft fleet. When we get on and off a plane safely, it's because of the work that you are doing. No one is going to call you to thank you for an event free flight. But you should know that there are many of us out there that do appreciate your efforts and we thank you each time we fly. I will make this pledge. You keep working to keep air travel as safe as possible and I will continue to work in the Congress on your behalf.

Our society is at times complacent. Until we have a crisis in front of us, we do not make things a priority. But I am not going to let this happen to aviation safety. There are too many lives at stake; witness what just happened in the Senate on our highway safety issues. We have repealed the 55-mph speed limit; we have repealed helmet requirements for motorcycle riders. I hope that when the statistics show that we have had increased injuries and deaths as a result of these actions, that Congress will come to its senses. The work of this organization and its accomplishments have made air travel ever safer. And I know that you are committed to continuing your important task. I am in your corner. I thank you and I wish you a productive conference.

Introductory Remarks

Honorable Pete Domenici (D-New Mexico)
(Presented by Chris Seher, Conference Chairman)

Thank you for your invitation to participate in the Sixth International Conference on Continued Airworthiness of Aircraft Structures. I regret that due to the Senate remaining in session and my work to complete the fiscal year 1996 balanced budget resolution, I am unable to be with you today.

I want to commend the Federal Aviation Administration and the National Aeronautics and Space Administration for hosting this international conference. I want to congratulate all conference participants for the important work you do to ensure the safety of the traveling public. As you look back upon your accomplishments, I know there are many successes and a strong foundation for future efforts.

I first became interested in your work when an opportunity arose for a collaboration between the FAA and the Department of Energy National Laboratory - Sandia National Laboratories - in Albuquerque, New Mexico. This collaboration will assess the use of technology in the inspection of aircraft and develop new technologies to improve the inspection of aging aircraft. With a fleet of aircraft that is aging and significant numbers of aircraft reaching their anticipated life cycles, it is critical that we are able to evaluate aircraft airworthiness through improved inspection technologies and techniques.

I am extremely pleased to say that this collaboration - in the form of the Aging Aircraft Nondestructive Inspection Validation Center - has been a success story. The FAA and the Department of Energy have blazed a new path of successful interagency cooperation. Industry cooperation has been a key factor in this partnership.

The Aging Aircraft Center has done an outstanding job working with the airlines, aircraft manufacturers, aircraft inspectors, and researchers to put together a program that already has a significant list of accomplishments. This Center holds the promise of major, world-class

achievements in the area of aircraft safety. This effort is a fine example of personal dedication. It shows the progress that can be made through interagency cooperation and represents a partnership that provides for the transfer of technology to industry for the general welfare of the American people.

The collaboration I speak of is but a small part of the effort underway by the dedicated people at this conference. I congratulate all of you for the outstanding work you do to ensure the safety of the traveling public. Thank you for your invitation. Thank you for the important work you do for all of us.

Maintaining a High Level of Safety in the Midst of Government Streamlining

David Hinson
Administrator
Federal Aviation Adminsitration
(Presented by Frank Elbertson, Acting Director, FAA Technical Center)

I am honored and pleased to have been invited here to give one of the opening addresses.

On behalf of the men and women in the FAA, I want to say thank you for your continued enthusiasm in our cooperative efforts to maintain the airworthiness of older airplanes. I am pleased to see so many of you participating in this, the sixth in a series of annual conferences.

I'm proud of the accomplishments you in industry and the men and women of the FAA have made to date in the aging airplane program. I hope that we can continue to work together in the future as we address these same aging issues on the current production and future design airplanes that are our aging of tomorrow.

I know you must be wondering about all of the changes in Washington and what effect they will have on the FAA and our regulatory programs.

You know the aviation system. So, it won't surprise you, when I say the demands on the FAA are greater today then ever before. We expend the majority of our resources on operating an air traffic control system. That system handles an average of two flights per second, every minute, every hour, 365 days a year.

With our assistance, June 27, 1995, the U. S. Commercial aviation fleet will move approximately 1.5 million passengers safely to their destinations.

Our safety, security and airport professionals will conduct nearly 1,000 inspections on an average day.

Safety is our top priority, and it permeates everything we do. But, safety is a shared responsibility.

We have the safest system in the world because of the men and women in the FAA. They are some of the most dedicated, hard-working safety professionals that I have ever seen.

We have the safest system in the world because the people working in aircraft manufacturing plants and their CEO's have worked hard to deliver and support a safe aircraft.

We have the safest system in the world because the airline employees and their CEO's work diligently to operate and maintain safe aircraft.

We have the safest system in the world because the airport director's and their employees have worked hard to establish and maintain a safe environment for aircraft operations.

And we have the safest system in the world because so many of you in this audience have conducted the research and developed the technology that we in the operating arena need as the basis for our efforts.

We've come a long way with this transportation system of ours. Someone told me recently that if we applied the accident rate from 30 years ago to today's traffic volume, we would average an airplane accident every two days.

So, despite what the cynics say, and the critics do, and the headlines read; they simply can't dispute one fact: Our aviation system out performs all others in safety and number of passengers served.

The question is: Can it be even better? Absolutely! We must make it better to retain this world record accomplishment. And that is the very reason we have established a new safety objective of zero accidents -- and are now taking steps to move aggressively towards that goal.

But, we, along with all other federal agencies, are being asked to do more with less, to become better custodians of the public's trust.

Over the last two years, we have responded by reducing our FAA budget by more than 6%, some $600 million. That would be an okay accomplishment, except that aviation traffic has grown by more than that 6% figure.

We've been able to manage through this interesting and challenging time by eliminating technology programs that are no longer warranted, by overhauling those that are going to cost too much, by reducing our work force as much as 5,000 employees, and by reorganizing the Agency so that we can better manage for results.

But we are now reaching a point where the FAA may no longer have the funds needed to do the job that the public expects us to perform.

Right now, the House and Senate are preparing to conference over their respective versions of achieving a balanced budget by 2002.

While I can tell you that we honestly do not yet understand in "high resolution" the full impact of these two budget proposals, we do know this: The magnitude of the cuts being proposed will have a devastating impact on aviation unless we change the way we do business.

The Senate budget is particularly troubling. It assumes the traveling public would pay an additional $14 million in taxes and fees to get the same level of service offered today.

We could be forced to cut 13,000 FAA jobs by 2002, with immediate cuts in fiscal year 1996. So far, we've been able to protect our safety work force from the budget ax. But cuts of this magnitude simply cannot be absorbed by just chopping overhead or administrative staff.

We could lose nearly 20 percent in our capital investment accounts, which would seriously delay new safety technology. Every program -- aviation safety to weather and windshear detection -- would be affected.

And something closer to home for you is the very real possibility that the National Aging Aircraft Research Program may be severely reduced or eliminated. We may not have the resources to establish a prediction capability for widespread fatigue damage -- a serious threat to our aging fleets TODAY.

Yes, we've survived the threat of such Draconian proposals before.

But, counting on the idea that FAA will survive these cuts in today's political climate because we are somehow unique ... because our mission is so critical ... is terribly risky.

It was this combination of personnel reductions, budgetary restraints, and ever-growing demand for our services that led to changes we have made and are continuing to make.

But streamlining alone cannot solve our problem.

In the history of the FAA, there have been 25 reorganizations. Yet due to federal laws and regulations that have built up over the years, we continue to manage contracts, allocate money and handle personnel as we always have.

It is not a very efficient system.

We take 19 months to develop an annual (twelve month) budget. Even then, we don't really know how much we will be allocated until the end. All because FAA is included in the federal budget.

It takes years to bring in a new, sophisticated technology. Often, when our air traffic controllers get their hands on it, the technology is already outdated. This, all because FAA is subject to the federal procurement laws.

It takes stacks of paper to process simple personnel actions and months to recruit personnel for desperately needed job functions -- all because the FAA is subject to federal personnel laws.

What we need is a new organization.

The Clinton Administration has proposed a solution. It's a not-for-profit, government-owned-and-operated U. S. Air Traffic Services corporation.

This corporation would be free from federal budgeting, procurement, and personnel actions. The users would fully fund and pay for 100 percent of its operating costs. They would use the fees

and taxes that they are currently paying for parking and fuel. And -- like other businesses -- the corporation would be able to borrow money to finance major capital improvements.

Congress has offered other alternatives for FAA reform. And, while we may have our differences on the best solution, the good news is that there is a broad consensus that the time has come for a change. We have to get on with the job of assuring the future growth of aviation in the United States.

Finally, before I depart, let me close by saying this about the FAA's aging airplane program. It is programs like this one that enable you in industry and us in government to work together in effectively accomplishing our safety goals in an open and productive environment.

A New Paradigm for Research and Acquisition

Dr. George L. Donohue
Associate Administrator for Research and Acquisition
Federal Aviation Administration

As Associate Administrator for Research & Acquisitions, I am in charge of a 2,000 member organization responsible for research, design, development, acquisition, and implementation of the infrastructure of the National Airspace System (NAS). This organization includes engineers, scientists, technicians, analysts, and managers. Approximately half of them reside at the FAA's Technical Center at Atlantic City, New Jersey.

Before discussing the organization in any more detail, let me try to put it in context so you can see the magnitude of the task we are engaged in.

The NAS system is a very large complex system that serves not only the airlines, but more than 175,000 general aviation aircraft as well--business aircraft, medivac operators, and private aircraft. In addition, it must also accommodate the needs of some 10,000 military aircraft.

There are 25,000 facilities in the NAS system that are continually in the process of being updated or replaced. Included in this inventory are some 470 traffic control towers, 21 air route traffic control centers which handle traffic in en route airspace between airport terminal areas, and a network of 130 or so flight service stations which provide a variety of preflight and in-flight information services, such as weather briefings, mostly for the general aviation community.

A modernized NAS system is critical to an industry which in turn is vital to the Nation's economy. Aviation and related industries contribute nearly $700 billion yearly to the economy and provide 8 million jobs. In a single day, air traffic handles upwards of 200,000 takeoffs and landings at airports across the county. U.S. airlines fly some 500 million passengers per year. This figure is expected to jump to 800 million over the next decade and reach the billion mark by the year 2015.

Over the years, FAA's research, engineering and development activities have played a vital role in helping the United States establish the safest and most efficient aviation system in the world.

Today, this valuable research, engineering, and development work by FAA continues at our Technical Center and in cooperative research activities with NASA, DOD, universities, and other government agencies around the country and abroad. They cover the gamut from aircraft and airport safety to improvements in communications, navigation, and surveillance which are the cornerstones of air traffic management.

Basically, our R,E&D program is split between actions related to improving air traffic control and activities to support the agency regulatory responsibilities--airport technology, aircraft safety, system security, and environment/energy.

Many of you may be aware of the work that is being done here at the Tech Center in the National Aging Aircraft Research Program. The fleet is aging with large numbers being more than 20 years old. The future shows even more reaching this age or more, with replacement numbers currently being too low to fill the gap. But we must keep fleet operations safe. A major goal of this program is to transfer the results of research in the form of new technology to fill aircraft maintenance and certification needs to improve aviation. Let me give you an idea of what we are doing in this area.

One of the major challenges we are working on is to improve aircraft inspection techniques. The development of these techniques is carried out for the FAA at a number of institutions, including other Federal agencies and universities. A major player is the FAA Center for Aviation Systems Reliability (CASR), made up of Iowa State University, Northwestern University, Wayne State University, and Tuskegee University. The validation and technology transfer of techniques is done at the FAA's Aging Aircraft Nondestructive Inspection Validation Center (AANC) at Sandia National Laboratory.

This is an area of research and development that promises to enhance safety and yield huge benefits for the industry. Industry estimates, for example, that the cost of a major overhaul (D-check) averages between $5 and $6 million per aircraft. With each aircraft requiring a major overhaul every five years on the average, the total cost for the industry to conduct major overhauls for all airfares older than ten years ranges between $9 and $11 billion.

So, even a ten percent reduction in costs through enhanced inspection techniques could produce a savings of some $1 billion. And that 10 percent is a very conservative estimate, by the way. We think we can do a lot better than that.

We are looking at a number of promising techniques. One is a self compensating ultrasonic (UT) technique that might serve as an alternate means of complying with the current requirement for a visual inspection. This UT technique is being tested in the inspection of the lower tee cap in DC--9 wing boxes for corrosion and cracks. Currently a visual inspection takes approximately 800 man hours. With the UT probe inspection, that could be reduced to as few as 20-40 man hours. Northwest Airlines, with a fleet of 108 DC-9 aircraft, estimates they could save from $1 to $2 million over a period of two years in maintenance costs just for this particular inspection.

We are also looking for reliable and cost-effective new methods or improvements in existing methods for detecting cracks, inclusions, and imperfections in titanium used in aircraft engines. The Tech Center, along with the FAA's directorate for aircraft engines in New England, has formed a consortium with the FAA Center for Aviation Systems Reliability (CASR), General Electric, Pratt & Whitney, and AlliedSignal Engines. The consortium has been asked to identify appropriate R&D to make this happen and it has already made significant headway in this area.

Now let me discuss for a few moments some of the other areas in our R&D program:

The work done by the FAA in fire safety research and aircraft crashworthiness has been a major factor in reducing injuries and fatalities over the past two decades. Tragically, in the past, there were far too many examples of passengers who lost their lives because of inadequate protection from passenger seats and moorings or who survived the initial impact of an accident only to perish in the post-crash environment as a result of fire. Over the past several years, hundreds of passengers owe their lives to the R,E&D work of the FAA in improving cabin safety.

Likewise, many lives are being saved by airborne collision avoidance systems which are the direct result of careful, painstaking research, engineering, and development work by the FAA with the cooperation of the airlines. Today, TCAS-II systems are required equipment on airliners

with 30 or more seats and, as the testimony of airline pilots will attest, they are an invaluable tool in warning pilots of potential midair collisions.

Another success story in aviation safety is the result of work done by FAA with NASA and in partnership with the airlines in better understanding the deadly effects of windshear and how to avoid it. The development of a training package for airline flight crews enabled US carriers to go more than ten years without a windshear-related accident following the 1985 accident at Dallas/Fort Worth in which 134 were killed.

In the area of navigation, the FAA is about ready to award a contract for the development of a wide area augmentation systems that will make the DOD-developed Global Positioning System (GPS) satellite system more useful for civil aviation. GPS is arguably the most important step in the history of navigation, and certainly the most significant innovation in air traffic control since the introduction of radar following World War II. Much of the testing for the wide area augmentation system was done at the FAA Technical Center.

In the fall, FAA-sponsored oceanic data link operations will begin in the Pacific, ultimately leading to a situation where satellite communications to transmit aircraft position data derived from GPS directly to controllers via data link. On June 21, FAA and Qantas Airlines successfully completed the first in a series of operational trials over the Pacific. Qantas initiated the test on a route between Sydney, Australia, and Los Angeles, using a Boeing 747-400 equipped with a new FANS-1 on-board computer communications package designed by Boeing and Honeywell.

While Qantas was communicating with the Oakland Center via a new oceanic ATC system, a test team at the Tech Center linked to the Oakland Center was shadowing the flight on a HF frequency radio to verify the proper operation of the new satellite-based equipment.

Later this summer, a number of other airlines, including United, will join Qantas in these tests in preparation for a prototype oceanic data link system to begin operation at a single sector at the Oakland Center, beginning in late September.

This program promises early benefits in transoceanic operations, one of the fastest growing segments of aviation. Here again, the application of data link for air traffic navigation, surveillance, and communications is the direct result of hard work by FAA engineers, technicians, and analysts working with the air traffic control operators to bring benefits measured in the billions of dollars to our customers, the users of the system.

Finally, R,E&D improvements in automation tools to help manage the flow of air traffic control nationwide have made a tremendous difference in reducing delays and minimizing the exposure to risks associated with airborne holding. R,E&D improvements in flow control automation capabilities contributed to a 33 percent reduction in flight delays during the 1989-1993 time frame. And delays have continued to decrease as we continue introducing improvements to air traffic management automation.

Yet, despite the notable successes in FAA's R,E&D program over the years, what I found when I came to the FAA last year was a program substantially out of sync with today's emerging realities. The real question was not whether the FAA had made valuable contributions to aviation in the past. That goes unquestioned. It was whether the FAA's organization and processes were in line with the rapidly changing world of technology and the dynamic needs of our customers.

The FAA is facing an enormous challenge. At a time of shrinking Federal resources and growing customer demand, we must replace aging equipment and systems on a broad scale throughout the entire NAS system--in the tower, terminal, and en route areas--virtually all at the same time. Many are no longer supportable from an economic point of view and they lack sufficient flexibility to accommodate future growth and the enhancements needed to meet spiraling demands.

Much of this is related to the way the FAA historically has done major system procurement. Traditionally, acquisitions have been geared toward a major systems acquisition approach, based on 15-20 year technology life cycles prevalent in the 1960's and 1970's. Today, with computer technology life-cycle down to 2-3 years, the agency has been put in the position of fielding

systems and equipment that are obsolete by the time they are installed. Over and above this, the FAA has had the additional difficulty of bringing technology from successful R,E&D into system acquisition and subsequent deployment.

So, clearly, we needed to do something to change this paradigm. When I came to the FAA last summer, I found research scattered all over the organization, disconnected in most cases from development activities, and not in line with a coherent acquisition process. So, as a start, I put in place a new organization this past fall and we are now in the process of changing our processes to go along with this new structure. The organization pulls together research, prototype, system development, and acquisition activities at the FAA into what I like to describe as a seamless process. It provides integration across functional lines and replaces a hierarchical, stovepipe organization with a flatter, horizontal structure which emphasizes empowering employees and placing decision-making and accountability at the lowest levels.

Reporting to me are seven senior managers, three of which are in charge of programs developed along product, rather than functional lines (see Figure 1). Key to this new organization are integrated product teams (IPT) which bring together representatives from functional disciplines: research specialists, air traffic, airway facilities, logistics, testing and contract personnel, system and specialty engineers, lawyers, and others, to focus exclusively on delivering products. IPT's have life-cycle responsibility for their products. This responsibility stretches from applied research through acquisition and beyond, to the point of making sure that products are up and working properly after they have been delivered and installed in the field. Key to this is membership by representatives from the air traffic operating and maintenance services to identify functional requirements from the very beginning of the life-cycle process.

Absolutely critical to the entire process is early and sustained involvement on the part of our customers--general aviation, business flying, and airline representatives. We must have them at the table from the very beginning of the process to help us define requirements and work hand and glove with us throughout the development and implementation phase to make sure we stay on track. In the past, successful research prototype efforts took years to put back into the acquisition process for eventual fielding, often after the technology was already obsolete.

In addition, we are getting away from the costly and time-consuming systems development approach, from a mentality that says if the FAA doesn't design it and develop it from scratch down to every minute detail, it won't serve our purposes. Instead, we are moving towards COTS/NDI acquisitions whenever possible and adapting equipment and systems to meet unique FAA operational requirements, as needed. By the way, COTS/NDI is shorthand for "commercial off-the-shelf, non-developmental items." I thought it was particularly important to clarify NDI for this group which might think it means "nondestructive inspections."

I assure you I make no pretense about this particular organizational structure being a silver bullet, or a panacea, in and of itself. What is key--no matter what the organizational structure looks like or what you call it--is the establishment of rigorous metrics and an evaluation mechanism to make sure the organization is meetings the goals and objectives we set out for it. We are now in the process of implementing these. As I said last fall when setting up the new organization, I plan to take a careful look at this organization a year from its establishment and make whatever changes are necessary. I might also add that I am committed to staying a minimum of five years to see this through. I believe a continuity of management at the executive level is critical to making the kind of systemic changes that are necessary.

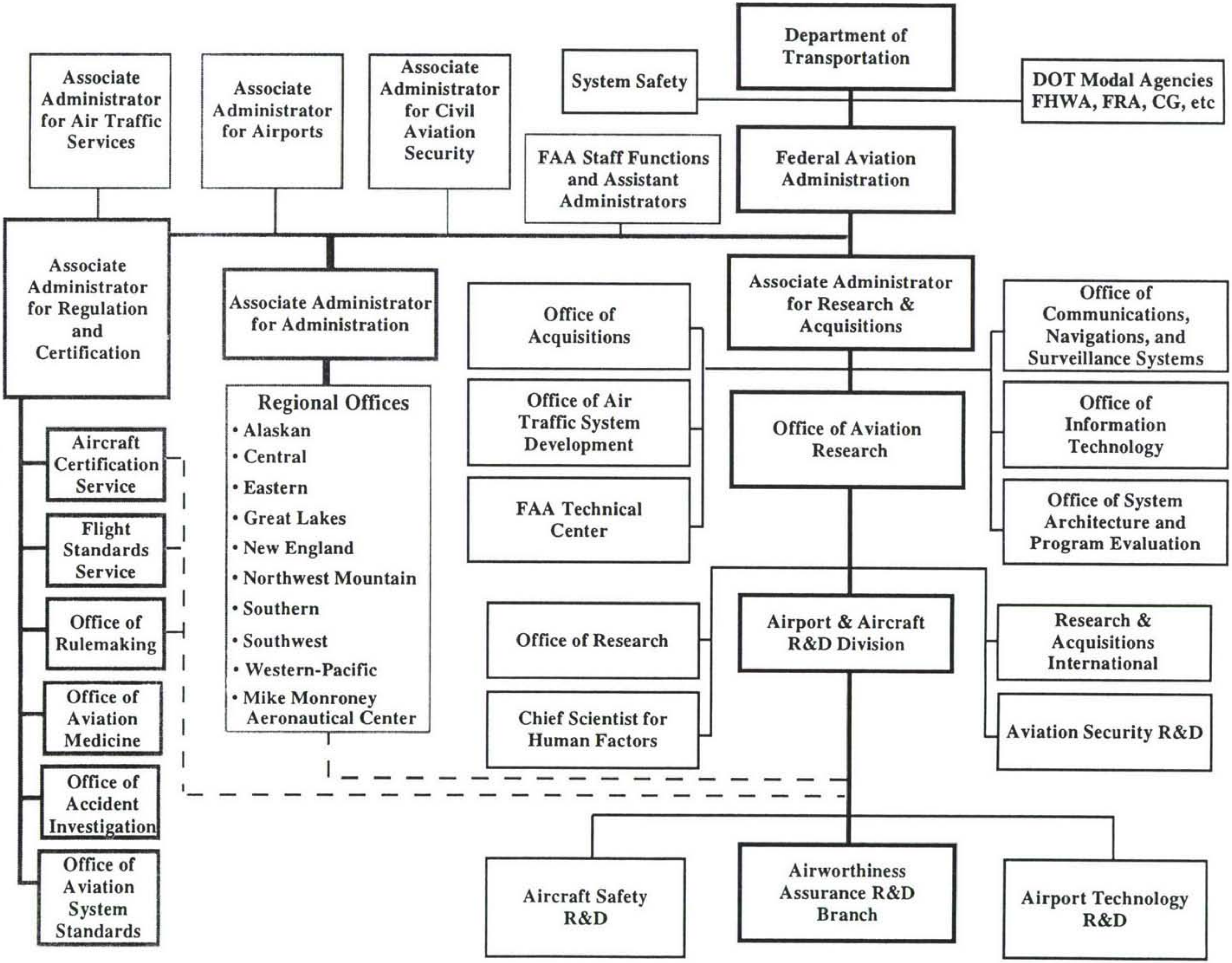
We have a tough challenge ahead of us particularly in light of the budgetary situation. But, as a recent *Economist* article on the defense technology stated, "these straitened times might seem to offer little prospect of radical innovation. In fact, they provide an excellent opportunity." It's a challenge that requires thought and creativity. As the article notes, "Such thought is the consequence of tight budgets that rule out solving problems simply by buying large quantities of bigger, more expensive weapons." Or "equipment," as the case may be. The principle is the same.

A key element to going about this process in a thoughtful, creative manner is the development of a National Airspace System architecture. Strange as this may seem, the FAA has never had a systems architecture *per se*. We have had plans and lists of programs and visions and mission statements, etc. But, we have never had an architecture which I believe is crucial to developing a rational, coherent national airspace system. We are now in the process of developing one. This

is my highest priority, particularly at this time of shrinking budgets when we need to make the crucial decisions on which programs we need to continue and which ones we can no longer afford. We cannot do this logically without a system architecture.

This week, in Washington, we are meeting with the users of the system to get their input so we can start fleshing out a system architecture which we plan to have in draft form in the September/October time frame. Later, in the early part of December, we have scheduled an international NAS systems architecture conference in Denver where representatives from Europe, North and South America, and the Pacific Rim countries will also have an opportunity to comment on the draft.

So, things are starting to come together. Not as fast as I would like, but that's one of the reasons I came to the FAA, to speed up the delivery of products and services. But, I am not discouraged. I think we have an unprecedented opportunity to shape the future system the way we and our customers think it ought to be. And our success will depend in no small part, as it has in the past, on R,E&D work carried out in partnership by FAA, NASA, and DOD.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Air Safety - Our Most Important Product as a Manufacturer

Margaret S. (Peg) Billson
Vice President - Technical Services
Product Support
Douglas Aircraft Company

Since 1988 the industry has undergone a paradigm shift in regard to the way structural maintenance programs are viewed. Has this improved safety or has it detracted from it? In this manufacturer's viewpoint safety has improved in every way. From the increased awareness of the significance of structural degradation, to the details of implementing a corrosion control program to maintain essentially corrosion free aircraft, safety has been enhanced. Douglas Aircraft Company is celebrating its 75th anniversary this year, and the record shows that our aircraft deserve their reputation as industry leaders in reliability and durability.

The following is a presentation of what we are doing to continue the heritage of the programs initiated in 1988 and how they are being extended to the newer certification programs like the MD-11 and MD-90. Safety, for the people who operate and fly on our products, is our most important product. The lessons learned in 1988, and since then, must never be forgotten.

BACKGROUND

In August of 1988, the Air Transport Association (ATA) and Aerospace Industries Association (AIA) in cooperation with the Federal Aviation Administration (FAA) established the Airworthiness Assurance Task Force (AATF). The AATF was commissioned to evaluate the deficiencies in the system that led to the April 1988 Aloha accident and to propose both industry wide and model specific actions to fix the system. Their charter extended to the oldest turbojet aircraft including the Boeing 707, 727, 737, and 747, Airbus A-300, BAC 1-11, Fokker F-28, Lockheed L-1011, and the Douglas DC-8, DC-9, and DC-10 (see Figure 1). The execution of the AATF charter has led to the institutionalization of programs dealing with:

1. Mandatory modifications for termination of repetitive inspections for certain critical service bulletins.

2. Industry-wide guidance for a mandatory corrosion prevention and control program.

3. Industry guidance on proper maintenance programs for aging aircraft.

4. Periodic audit of the Supplemental Inspection Documents(SIDs) to ensure that they contain all of the necessary inspection areas to preserve safety.

5. Damage tolerance assessment of repairs for older turbojet aircraft with attendant modifications of maintenance programs.

6. A voluntary audit of older turbojet aircraft for the determination of the probability of occurrence of widespread fatigue damage during an aircraft's projected operational lifetime.

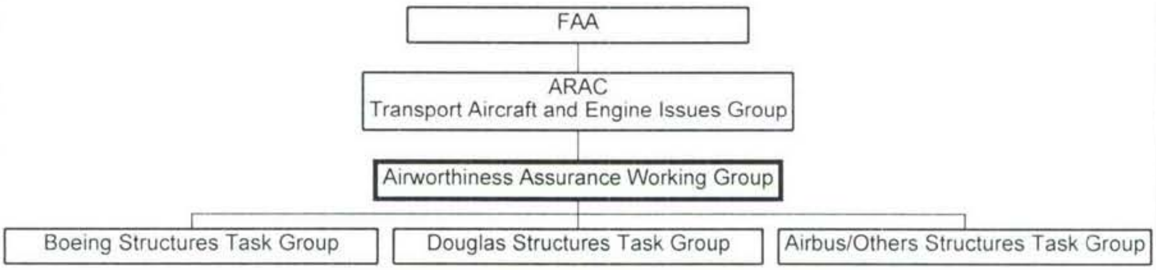

Figure 1 - AATF (AAWG) Organization

The AATF programs provide a means to upgrade an aircraft at a specific point in its life to insure that the original fail-safe design principles are intact on an aircraft by aircraft basis. The assurance of intact fail-safe design features provides the first line of defense against all forms of structural degradation such as fatigue, accidental damage, environmental deterioration, and discrete source damage (see Figure 2).

In 1992, the AATF was incorporated into the Aviation Rulemaking Advisory Committee (ARAC) as the Airworthiness Assurance Working Group (AAWG) under the Transport Aircraft and Engine Issues Group (TAEIG). Today the AAWG continues to be the authority on the six programs just identified.

IMPORTANCE OF FAIL-SAFE DESIGN FEATURES

TWO BAY CRACK ASSURES A LEVEL OF SAFETY AGAINST

- FATIGUE
- ACCIDENTAL DAMAGE
- ENVIRONMENTAL DETERIORATION
- DISCRETE SOURCE DAMAGE

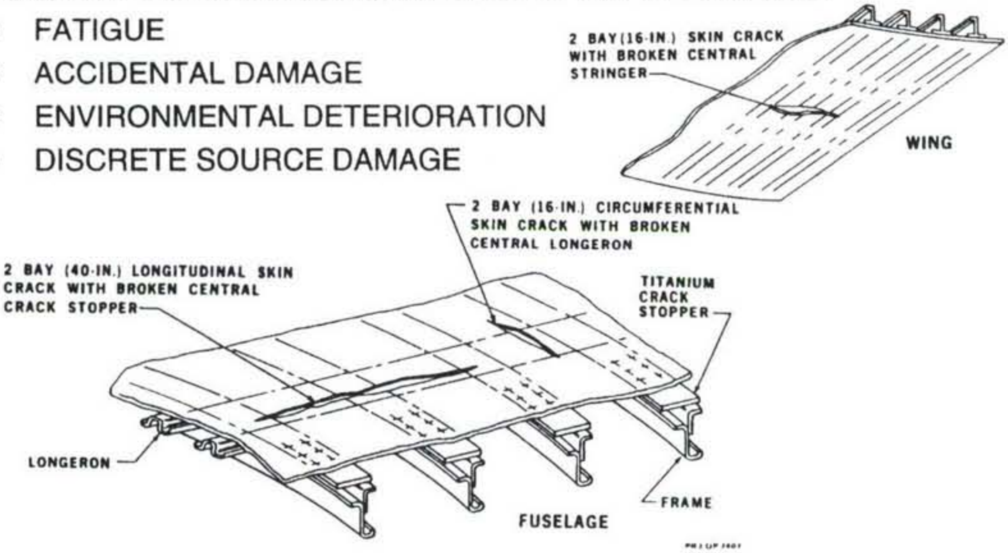

Figure 2 - Importance of Fail-Safe Design Features

DAC AGING AIRCRAFT PROGRAMS

The Douglas Commercial Jet Fleet - The Douglas commercial jet inventory status shown in Figure 3, reveals that of 3,234 aircraft produced so far, 2,863 are still active. Of the active fleet, over 1,167 have exceeded the original 20-year design objective. Some aircraft have exceeded thirty years of service. Also, 1,268 aircraft have exceeded the one lifetime design objective in terms of flight hours, and 780 have exceeded the one lifetime objective in terms of landings. None have exceeded the test supported life generally established as one-half of the fatigue tested life. Since the aging aircraft programs began, the MD-11 and MD-90 aircraft have been added to the Douglas fleet. While these aircraft are new, they have, as part of their certification procedure, had maintenance programs approved that embody a number of AAWG programs and concepts. Those programs and concepts will be addressed now.

Douglas, with the cooperation of operators and regulators throughout the world, has developed and/or participated in six interrelated programs to identify and address issues that are generic to an aging fleet of aircraft. The programs not only embody the AAWG initiatives but go well beyond those standards. These programs, are shown in Figure 4.

DOUGLAS COMMERCIAL JET FLEET

MARCH 1995

122,346,276 Flight Hours 85,629,226 Landings

Aircraft	Produced	Active	Initial Delivery Date	High Time Active Aircraft	Design Goals	Aircraft Exceeding Design Goals	Test-Supported Life	Active Aircraft Average Age (Years)
DC-8	556	309	1959	46,621 LDGS 86,223 FH 35.47 Years	25,000 LDGS 50,000 FH 20 Years	71 252 309	70,200 140,000	27.3
DC-9	976	888	1965	98,866 LDGS 78,638 FH 29.54 Years	40,000 LDGS 30,000 FH 20 Years	709 843 686	102,400 78,000	23.9
DC-10	446	419	1971	35,733 LDGS 90,332 FH 24.67 Years	42,000 LDGS 60,000 FH 20 Years	**3 173 172	42,000 60,000	17.3
MD-80	1,120	1,111	1980	41,210 LDGS 44,988 FH 15.09 Years	50,000 LDGS 50,000 FH 20 Years	0 0 0	50,000 50,000	6.9
MD-11	131	131	1990	4,013 LDGS 19,543 FH 5.22 Years	20,000 LDGS 60,000 FH 20 Years	0 0 0	20,000 60,000	2.5
MD-90	5	5	*1993	972 LDGS 1,182 FH 2.13 Years	60,000 LDGS 90,000 FH 20 Years	0 0 0	60,000 90,000	1.8
Total	3,234	2,863		0 50K 100K FH/LDGS 0 20 40 Years				

* Flight Test Delivery
** DC-10 Series 30/40 Design Goal 30,000 LDGS

Figure 3 - Douglas Commercial Jet Fleet

DOUGLAS APPROACH TO AGING AIRCRAFT SAFETY

- **SIX INTERRELATED PROGRAMS**
  - SUPPLEMENTAL INSPECTION PROGRAMS
  - EXTENDED AIRFRAME FATIGUE TESTING
  - DOUGLAS DESIGN EVALUATION PROGRAM
  - AIRWORTHINESS ASSURANCE WORKING GROUP
  - TRAINING
  - FAA-NASA RESEARCH AND DEVELOPMENT PROGRAMS FOR AGING AIRCRAFT
- **EACH SUPPORTS AND ENHANCES THE OTHERS**

Figure 4 - Douglas Approach to Aging Aircraft Safety

Some of the programs are passive in that they act as a source of data to evaluate the structural health of the fleet. These programs include the Extended Fatigue Test Programs and the Douglas Design Evaluation Program The data from these programs are used to adjust, as necessary, active programs. Active programs include the Supplemental Inspection Document program and the programs developed as a result of the AATF initiatives discussed earlier. These programs perform specific tasks on aircraft in the fleet. Training, which is interactive, is also included among the aging fleet programs because there is, as always, a need to ensure a common level of understanding across the industry.

All of these programs establish a basis which supports the timely detection of all forms of structural degradation. Interaction is needed between the various parts of the industry to insure the structural integrity of the aircraft. Each party has its own specific role in assuring that integrity. The manufacturer supplies the necessary technical support in evaluating service findings. The operator is ultimately responsible for aircraft maintenance. And the regulator insures that the regulations are being followed by both the manufacturer and the operator and enforces compliance on critical safety issues. The key ingredient to this system is communication among all parties (see Figure 5).

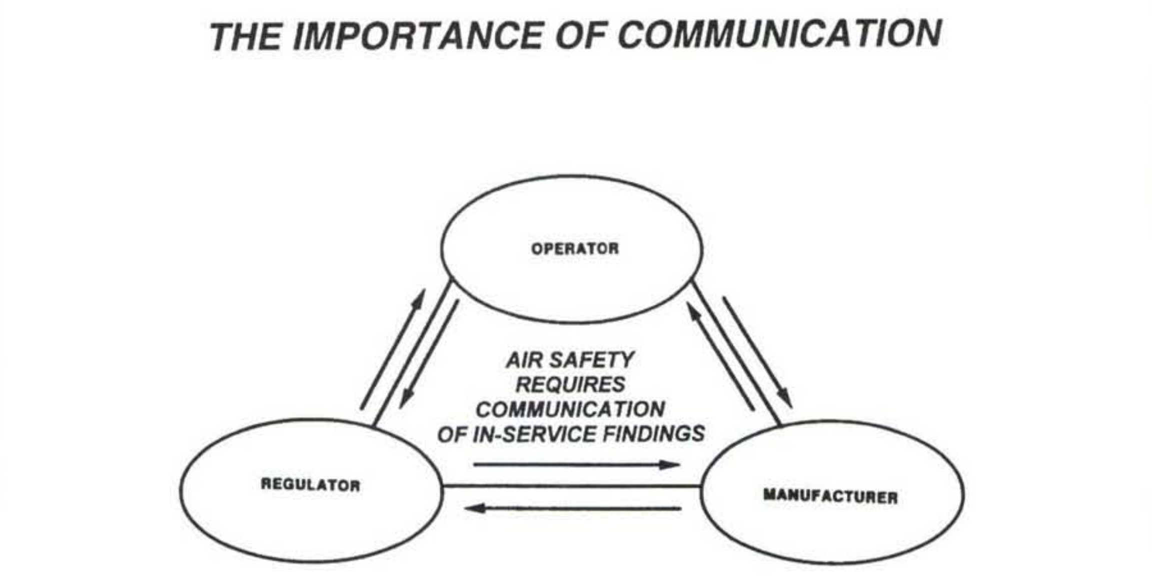

Figure 5 - Importance of Communication

As mentioned earlier, there are six interrelated programs that have been adopted by Douglas Aircraft Company to ensure continued airworthiness of the Douglas Jet Fleet. The first is the supplemental inspection programs.

Supplemental Inspection Programs - (Figure 6) - In 1978, the British CAA published Airworthiness Note Number 89, which detailed the criteria to be met in performing a structural audit on aging aircraft. These criteria represented an acceptable means to remove CAA imposed life limits on aircraft operated in the UK. In 1981, the FAA published Advisory Circular 91-56, which provided guidance on how an operator, with the cooperation of the manufacturer, could provide supplemental inspections similar to those required on aircraft certified to FAR 25.571 Amendment 45 requiring damage tolerance evaluation. Both of these documents directed the development of the Supplemental Inspection Document (SID) programs. The intent of the SID program is to augment the routine maintenance program in order to detect fatigue damage in areas where fatigue is likely to occur in the future.

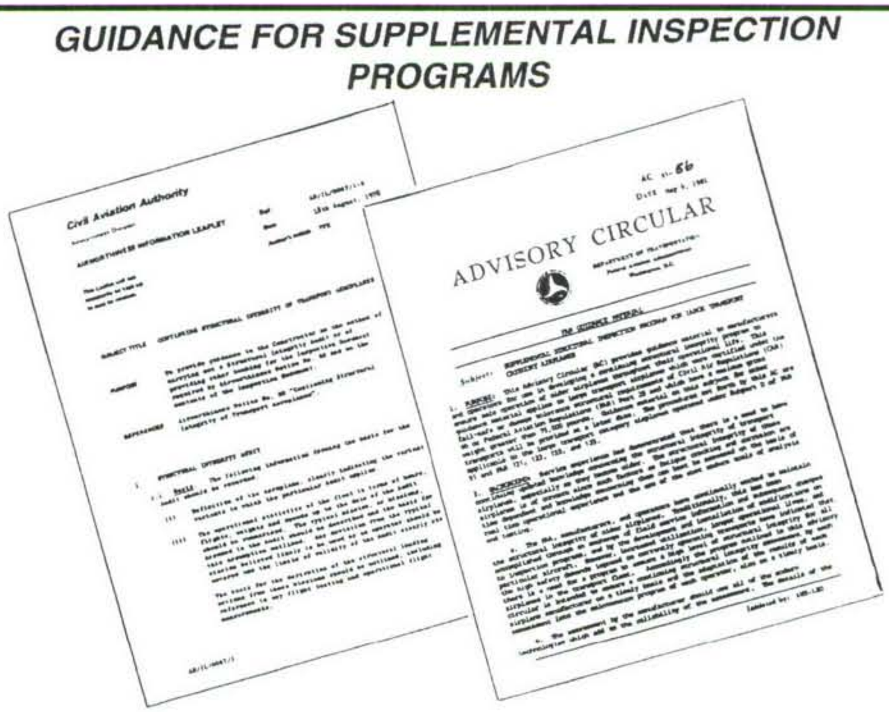

Figure 6 - Guidance for Supplemental Inspection Programs

In the development of the SID program, two separate criteria documents were developed by Douglas and approved by both the FAA and CAA. The first document detailed the means by which the damage tolerance analysis would be conducted. The second document detailed the implementation of a sampling program based on a zero defects sampling concept. The second document also addressed with the development procedures to insure reliable nondestructive inspection programs, inspection thresholds, and areas of inspection. The procedures detailed in these two reports established the goal of 99% probability of detecting fatigue damage before it becomes a safety hazard with an attendant maximum probability of 1×10^{-9} per flight of a catastrophic event occurring. The details of the Douglas SID program are shown in Figure 7.

DOUGLAS SUPPLEMENTAL INSPECTION PROGRAM

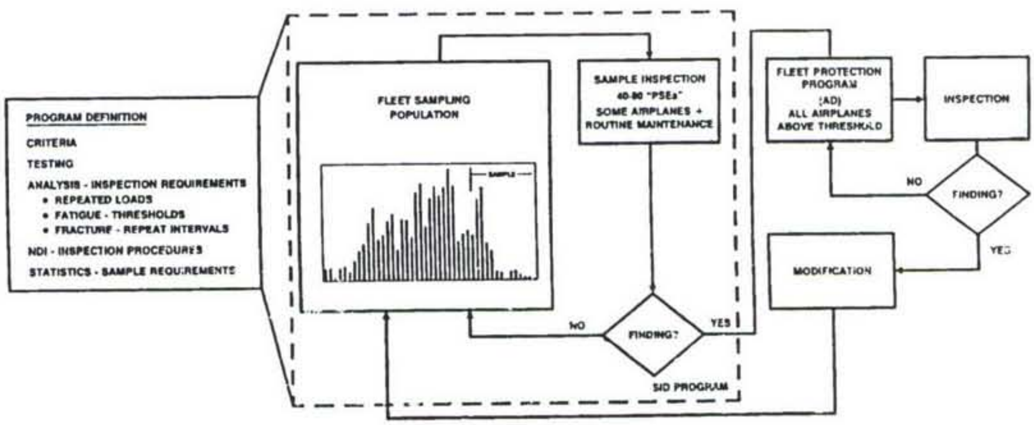

Figure 7 - The Douglas Supplemental Inspection Program

Extended Airframe Fatigue Testing - The second area that Douglas has adopted for maintaining continued airworthiness of the aging fleet is extended airframe testing. When an aircraft is initially proposed, the design of the aircraft is estimated assuming on a 20-year economic life and a specific utilization. These estimates are based on the customer's anticipated use of the aircraft and are used to establish structural design requirements. Invariably these estimates do not totally predict how the aircraft is ultimately used in service. Variations in the way the aircraft is used between operators

may mean that at some point the developmental fatigue test that was conducted using the pre-service estimates may not adequately shelter the active fleet. At this point, it can be helpful to conduct new fatigue test of the structure to characterize the fatigue behavior of the aircraft. The new fatigue test, as it surpasses the original test life, can reveal potential new problem areas that have not yet developed in service This will allow the manufacturer to raise these issues with the airlines and regulators so that appropriate fleet action can occur such as augmentation of the SID programs or the issuance of a service bulletin.

The DC-9 (Figure 8) was the second jet transport introduced by Douglas. First production models of the aircraft were designed to carry 70 to 90 passengers over short routes. Later models increased both passenger and range capability. First introduced in 1965, derivatives of this aircraft (MD-80) are still being produced with production plans that extend to at least the year 2000. Several DC-9 high-time aircraft are well into their third design life as far as landings are concerned. Fourteen years ago this prompted Douglas to do some special tests to assure the fitness of the aircraft for extended service.

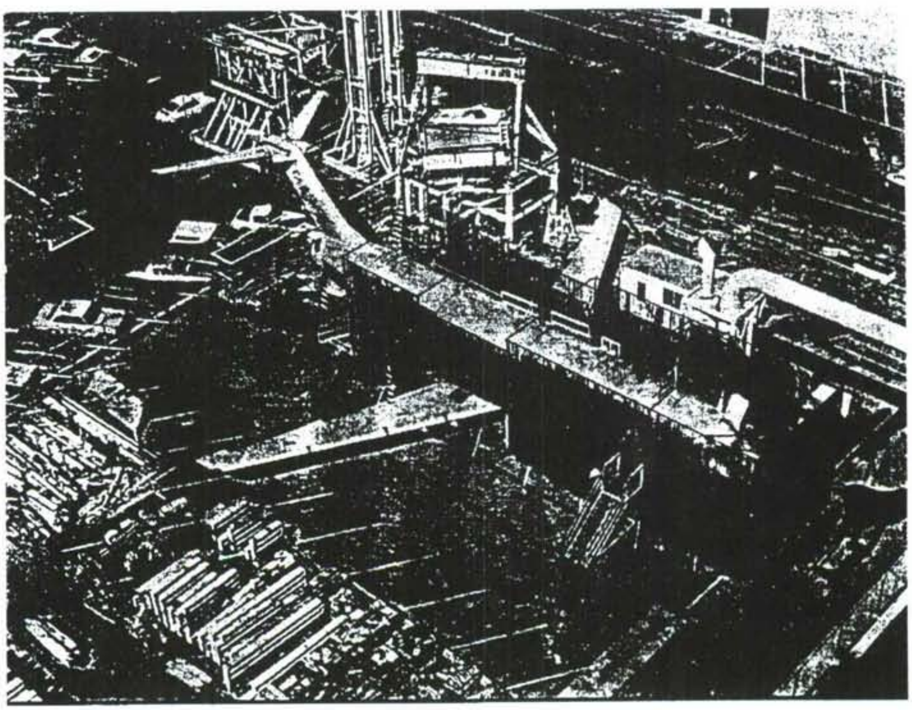

Figure 8 - DC-9 Fuselage Number 3 Extended Life Test

In 1981 Douglas purchased DC-9 Fuselage Number 3. At the time it was one of the five high-time aircraft and had accumulated over 66,500 landings. It was in regular airline service and was accruing landings at the rate of 3500 a year. At the time, it was scheduled for a major structural maintenance check (D check) within a month. The aircraft was stripped of interior items and a thorough inspection of the structure conducted. After a total of 15 years of service, the structure was remarkably free of corrosion and fatigue cracks. The problem areas found were either repaired or tagged for careful evaluation as the test progressed. Certain service bulletins were selected for incorporation before the test began.

The testing extended the test supported life on the DC-9 fuselage structure from 125,000 flights to over 208,000 flights. After the test an extensive evaluation of the structure was conducted including "tear down" of over 22 feet of fuselage longitudinal lap splice (Figure 9). Over 8000 individual rivet holes were checked for fatigue cracks with no findings, indicating a freedom from the development of Multiple Site Damage (MSD) for that type of design. In addition, after 20 years of service, there was no reported corrosion found in the faying surface. Additional tear-down inspections and coupon type fatigue tests on the wing and empennage structure extended the test supported life of these components to over 208,000 flights. The testing conducted on the DC-9 provides a high degree of confidence that the structure will be relatively crack free until at least 102, 000 landings.

<u>*Douglas Design Evaluation Program*</u> - From 1988 through 1991, Douglas launched it's third program to evaluate the continued airworthiness of aging aircraft. During this time, DAC conducted 16 trips to various operators to observe Douglas Aircraft undergoing heavy maintenance to assess the in-service condition of the airplane (Figure 10). This program was conducted in support of other aging aircraft programs. During each visit, an evaluation of the aircraft was made relative to the ease of maintainability, structural performance, and structural problem areas. The primary purpose of this evaluation was to provide insight into the areas where the design could be improved. Additional benefits

were achieved through direct operator communications and technical awareness of potential problem areas.

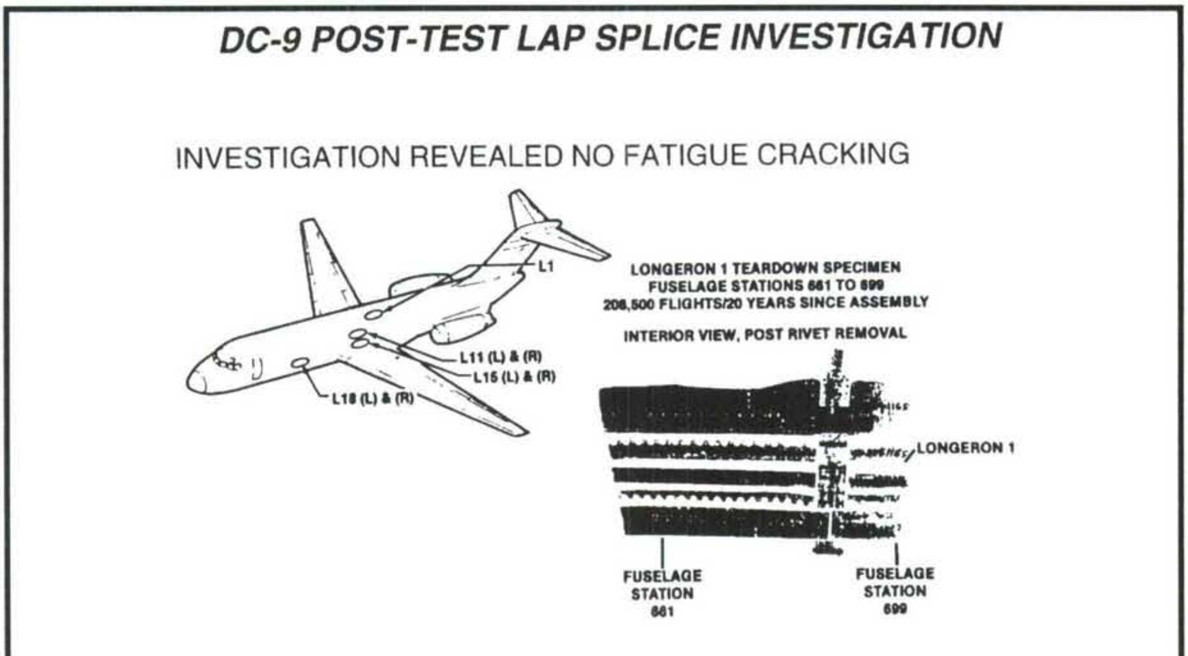

Figure 9 - DC-9 Post-Test Lap Splice Investigation

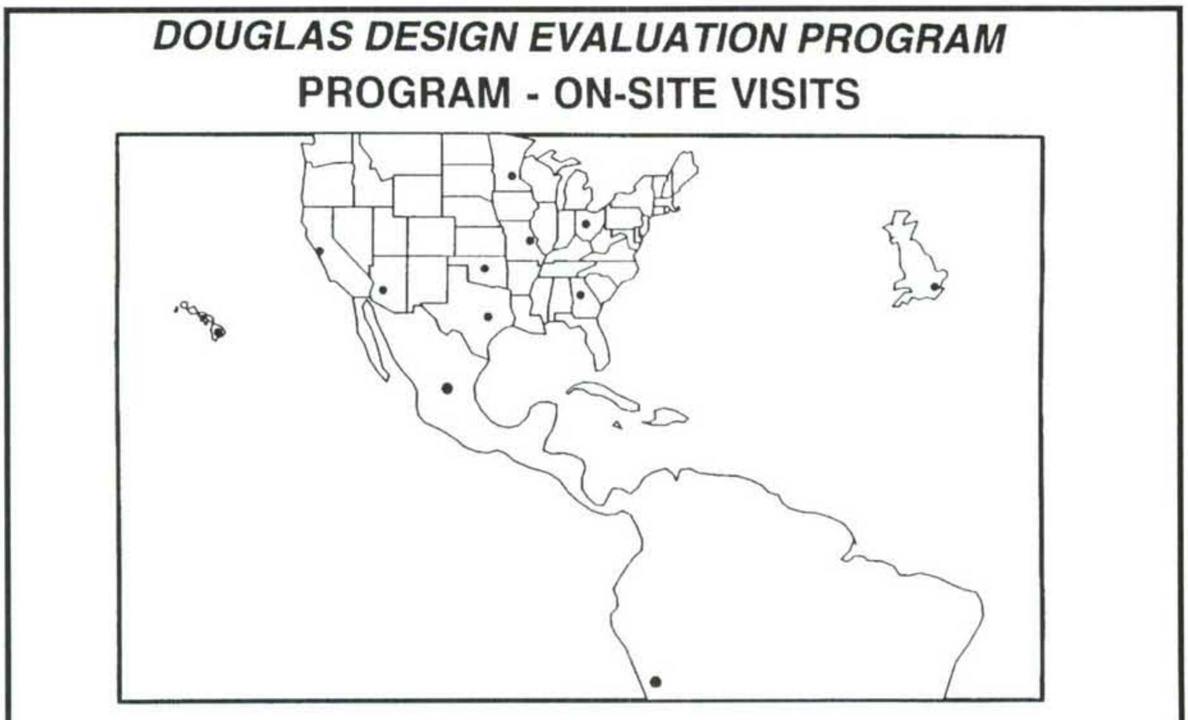

Figure 10 - Douglas Design Evaluation Program

A total of 20 aircraft were evaluated including the then high-time DC-9 aircraft. Each aircraft was evaluated in five areas by a team of six to ten technical specialists. The following summarizes the findings of the surveys (see Figure 11):

Fatigue - The aircraft observed in heavy maintenance did not show any signs of fatigue in areas not already previously identified.

Corrosion - Generally speaking, the corrosion prevention systems put in place as part of the IATA standards in the late 1960's are holding up remarkably well after 20 years of service. Earlier aircraft are likewise relatively free of corrosion as long as maintenance is performed in a timely manner. No interaction of corrosion and fatigue was observed in any aircraft. Several design improvements were incorporated as a result of the findings of small areas of chronic corrosion.

Maintenance Programs - The aircraft's maintenance program was evaluated relative to the degree that it had been modified from original recommended programs. It was found that the airlines have routinely escalated such programs based on the results of inspections conducted during the maintenance visits. These escalations are allowed by the regulator. Unlimited escalations, however, have been found to be detrimental to safety especially when there are time dependent phenomena that could alter the basic assumptions that allowed the escalation in the first place. Debonding of doublers and corrosion are examples of such time dependent phenomena.

DOUGLAS DESIGN EVALUATION
PROGRAM AREAS OF INVESTIGATION

- **FATIGUE**
- **CORROSION**
- **MAINTENANCE PROGRAMS**
- **REPAIRS**
- **SERVICE BULLETIN COMPLIANCE**

Figure 11 - Douglas Design Evaluation Program - Areas of Investigation

Repairs - Numerous repairs were observed installed on Douglas Products. While all of these repairs were determined to posses adequate strength capability, it was impossible to determine whether or not the repairs were adequate for damage tolerance, which is a concern for repairs identified in areas defined as Principle Structural Elements (PSEs). It was observed that a number of repairs utilized blind fasteners and/or alternate fastening systems.

Service Bulletin Compliance - Each aircraft was evaluated for the number of mandatory service bulletins that had been incorporated. It was determined that most operators preferred to inspect and repair on condition rather than install terminating modifications.

Airworthiness Assurance Working Group - Douglas has been an active member of the AAWG since its inception in 1988. It has provided the leadership to the industry in proposing several solutions to the issues with which it was tasked. As mentioned earlier, the AAWG was tasked with six initiatives for action across the eleven identified aging aircraft models. Douglas, together with the operators of the DC-8, DC-9, and DC-10 formed Structures Task Groups (STGs) to examine each task, propose solutions, and make recommendations to the AAWG. To date, the STGs have proposed programs for four of the six. The remaining two programs are still under consideration with planned implementation in the future.

The first area assigned to the STGs for consideration was the common industry practice of maintaining inspection programs in lieu of incorporation of structurally significant service bulletins.

Service Action Requirements Program. The AAWG identified a significant safety shortfall in the industry wide practice of allowing continued inspections for safety critical structural service bulletins. All service bulletins allow an option to inspect and repair on condition instead of installing a terminating structural modification. For certain service bulletins, this practice could allow operation of the aircraft with significant but undetected structural degradation. The AAWG identified three basic criteria (Figure 12)

to categorize service bulletins for the potential of undetected safety related structural degradation.

AAWG SERVICE ACTION REQUIREMENTS PROGRAM CRITERIA

- **SAFETY RELATED**
- **HIGH PROBABILITY OF OCCURRENCE WITHIN THE FLEET**
- **CONDITION DIFFICULT TO DETECT ON AIRCRAFT**

Figure 12 - AAWG Service Action Requirements Program Criteria

Service bulletins that met all three criteria were terminated from repeat inspection programs before safety issues could develop within the fleet. Well over 5000 structurally related service bulletins were examined for the Douglas DC-8, DC-9, and DC-10 aircraft. As shown in Figure 13, less than three percent were selected as meeting the above criteria. Yearly reviews are conducted on new service bulletins issued against the three models for determination as to whether or not the new bulletins need to be added to the program. The regulators chose to mandate the service bulletins selected by issuing Airworthiness Directives.

Mandatory Corrosion Prevention and Control Program - Fleet surveys, maintenance cost reviews, and comments received from operators all point to the issue that corrosion forms the largest investment in time and resources in an aircraft maintenance program. From all of these sources, it became obvious that some aircraft were being maintained in conditions below manufacturer's expectations. In some cases the aircraft's condition fell below the requirements for fail-safe.

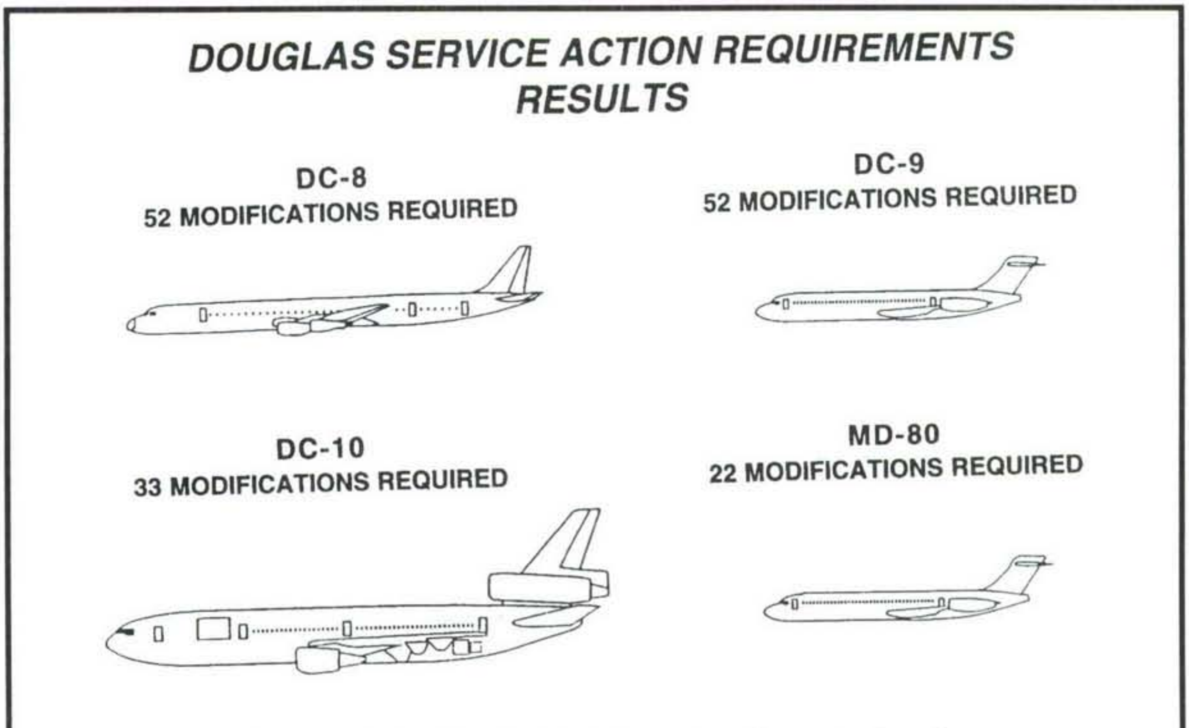

Figure 13 - Douglas Service Action Requirements Results

These revelations led the industry to propose new standards for corrosion prevention and control. These new standards, which proposed maintaining essentially corrosion free aircraft, were translated into an operational maintenance programs on an industry-wide basis. The new maintenance program identifies a specific maintenance task to be performed in every area of primary structure and establishes a baseline initial and repeat interval for the inspections to occur (see Figure 14). Areas that cannot be maintained essentially corrosion free require an operator to modify it's maintenance program and, if deemed significant, perform an inspection of all aircraft in its fleet.

THE AAWG CORROSION PREVENTION AND CONTROL PROGRAM

- **ALL PRIMARY STRUCTURE TO BE INSPECTED**
- **INITIAL AND REPEAT INTERVALS TO BE ON A CALENDAR TIME BASIS**
- **BASIC MAINTENANCE TASK TO BE PERFORMED**
  - **EXPOSE AREA**
  - **CLEAN**
  - **INSPECT**
  - **REWORK AS REQUIRED**
  - **REESTABLISH CORROSION PREVENTATIVE TREATMENTS**
- **REQUIRES MAINTENANCE PROGRAM ADJUSTMENTS IF SIGNIFICANT CORROSION FOUND**

Figure 14 - The AAWG Corrosion Prevention and Control Program

Corrosion prevention and control programs have been issued for the DC-8, DC-9, and DC-10. All of these programs are mandated by Airworthiness Directives which require the programs be adopted within operator's individual approved maintenance programs. Yearly reviews of the model specific programs are conducted with the operators to revalidate the baseline program.

Maintenance Programs For Aging Aircraft - In examining the issues surrounding the 1988 accident, the industry discovered that there was little guidance available for maintenance programs for an operator who was trying to maintain an aging aircraft. The AAWG authorized the production of a document with the help of the ATA, AIA, and FAA that provides the necessary guidance. This document is available from the ATA as ATA Report 51-93-01 (Figure 15).

Supplemental Inspection Documents (SID) Audit - The supplemental inspection programs were originally designed as the first line of defense against fatigue cracking that might occur within the fleet. The purpose of this audit was to determine if additional items needed to be added to the program since the program seemed to have failed on one aircraft in 1988. The basis of the review was to make sure that all primary structure was originally included in the document, and that none was eliminated due to the belief that

its failure would be "in-flight" evident. In the review conducted by Douglas, no deficiency was found in the programs for the DC-8, DC-9, and DC-10.

AIR TRANSPORT ASSOCIATION/INDUSTRY GUIDANCE MATERIAL ON AGING AIRCRAFT MAINTENANCE PROGRAMS

Figure 15 - Air Transport Association/Industry Guidance Material on Aging Aircraft Maintenance Programs

Damage Tolerance Assessment Of Repairs - The controls placed on the way aircraft are repaired have been generally less stringent than those required for original design. The reason for this is somewhat complex but has to do with the fact that Federal Aviation Regulations (FARs) are set up in such a way that the regulations used for design were more demanding that those for operation. This meant that repairs could be installed such that basic design concepts, such as fail-safe, could be compromised. While not a direct finding in the 1988 accident, the AAWG determined that this area was critical to safety and requested that a program be developed to address the on-going continued airworthiness of primary structural repairs.

The AAWG directed a fact finding activity (Figure 16) whereby a total of 65 in-service aircraft were surveyed for repairs to determine if continued airworthiness concerns existed. Over 1000 repairs were observed, of which 85% were on the fuselage pressure shell. The surveys also revealed that 60% of the repairs required inspections to preserve continued airworthiness. Based on these findings, the FAA requested that the AAWG develop an operational rule and guidance material for promulgation on the eleven AAWG models.

AAWG PROGRAM ON REPAIR ASSESSMENTS

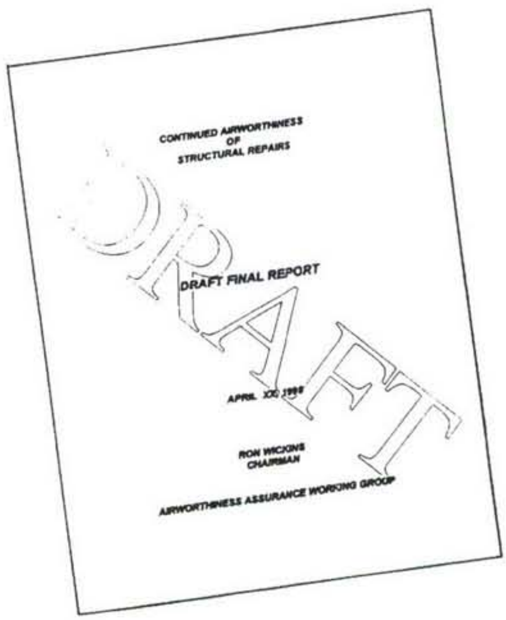

Figure 16 - AAWG Program on Repair Assessments

The operational rule with guidance material has been written for the repair assessment program. AAWG approval of this rule is expected in June 1995. After acceptance, the rule will be forwarded to ARAC for final coordination and publication.

Widespread Fatigue Damage Audit -In response to the NTSB findings on the April 1988 Aloha accident, the FAA proposed a new rule to further reduce the risk of a similar accident occurring. The proposed rule embraced a fatigue testing concept to protect the

fleet against the onset of widespread fatigue damage and was directed toward new certification programs as well as retroactive fatigue testing for aircraft already certified.

The AAWG, as well as the AIA initiated independent reviews of the proposed rule to assist the FAA in arriving at appropriate rule making material. Results of the Douglas led industry reviews indicate that while fatigue testing is appropriate for new certification programs, it is not appropriate, in and of itself, to protect older aircraft against the onset of widespread fatigue damage. Specific rules requiring fatigue testing of older aircraft may mean the premature and unnecessary retirement of many aircraft. The AAWG formalized their recommendations in the form of a report that advocated a voluntary assessment for the possibility of onset of widespread fatigue damage (Figure 17). These recommendations were submitted to ARAC in early 1994 and advocated the addition of guidance material to an appendix of Advisory Circular 91-56. Advisory Circular 91-56 currently provides guidance on the development of supplemental inspection programs for large transport category aircraft.

AAWG PROGRAM FOR WIDESPREAD FATIGUE DAMAGE

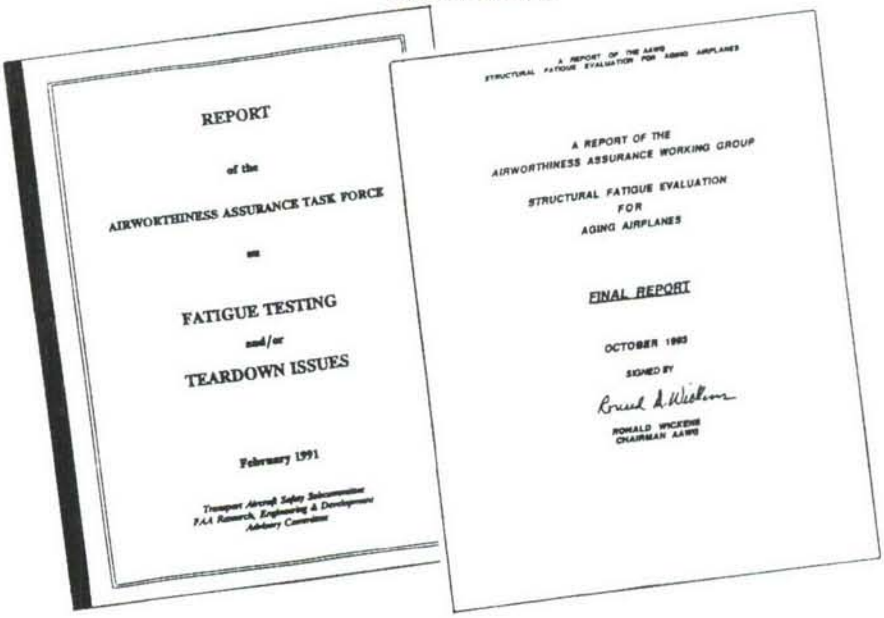

Figure 17 - AAWG Program for Widespread Fatigue Damage

Douglas is in the process of developing data to assess widespread fatigue damage issues on its aircraft for review in the model specific Structure Task Groups.

Training - An integral part of the aging aircraft program is that of training. New concepts were introduced as part of the overall aging aircraft program requiring training at all levels, from the Federal Aviation Administration Principal Maintenance Inspectors (FAA PMI), to the airline maintenance program planner (Figure 18). DAC has offered for the last three years, and is continuing to offer, aging aircraft program training for those operators that deem it necessary.

Review Of FAA/NASA Research And Development Programs - Douglas has been active in the review of ongoing FAA and NASA research and development programs for aging aircraft since the congress set aside funds for this purpose in 1988. Douglas considers this activity is extremely important in that this is one way in which it is insured that the R&D money is being properly spent in areas of most benefit to the industry. Douglas participates in twice yearly reviews of research programs with NASA and the FAA Technical Center, and is also active on the FAA Research Engineering and Development Subcommittee Aircraft Safety (Figure 19).

DOUGLAS AGING AIRCRAFT TRAINING PROGRAMS

REGULARLY SCHEDULED COURSES
- **SERVICE ACTION REQUIREMENTS**
- **CORROSION PREVENTION AND CONTROL**
- **AGING AIRCRAFT MAINTENANCE**
- **REPAIR DESIGN**
- **FATIGUE AND FRACTURE CONSIDERATIONS**

Figure 18 - Douglas Aging Aircraft Training Programs

REVIEW OF ONGOING AGING AIRCRAFT RESEARCH AND DEVELOPMENT PROGRAMS

- BI-ANNUAL DOUGLAS REVIEWS OF PROGRAMS
  - FAA
  - NASA
- PROVIDES MEANS FOR INPUT TO BASELINE R&D PROGRAMS AS AN END USER
- MEMBER SUBCOMMITTEE ON AIRCRAFT SAFETY - ANNUAL REVIEWS OF OVERALL R&D THRUSTS
  - FAA
  - NASA

Figure 19 - Review of Ongoing Aging Research and Development Programs

MAINTENANCE PROGRAMS FOR NEWER AIRCRAFT

The advent of new aircraft and new certification programs has presented an interesting challenge to manufacturers and operators on how to implement new maintenance concepts developed for the older aircraft. DAC has led the industry in proposing the means of incorporation of the AAWG concepts into the maintenance programs for both the MD-11 and MD-90 aircraft. DAC has been able to incorporate a great majority of the AAWG programs as part of the Maintenance Review Board process prior to certification. The programs embodied within the MRB process do not require separate Airworthiness Directives to insure operator compliance. Operator compliance is assured by the establishment of controls within the MRB that prohibit escalation of intervals for continued airworthiness programs without FAA Aircraft Certification Office approvals. These portions of the MRB document are required to be incorporated into the FAA approved maintenance programs for each operator. DAC has been successful in incorporating both the Airworthiness Limitation Instructions (equivalent to the SID programs for aircraft certified prior to 1981), and the Corrosion Prevention and Control Programs as part of the pre-certification activities (Figure 20).

MAINTENANCE PROGRAMS FOR NEW CERTIFICATION PROGRAMS

- **AAWG PROGRAMS INTEGRATED INTO THE MAINTENANCE REVIEW BOARD PROCESS PRIOR TO CERTIFICATION**
  - SUPPLEMENTAL INSPECTION PROGRAMS
  - CORROSION PREVENTION AND CONTROL
- **REPAIRS ARE DAMAGE TOLERANT BY VIRTUE OF THE CERTIFICATION BASIS**
  - SRM IS FULLY COMPLIANT
  - SPECIAL REPAIRS ARE REVIEWED PER FAR AC 25-1529-1
- **SERVICE BULLETINS ARE REVIEWED BY THE ATA AIRWORTHINESS CONCERN PROCESS PRIOR TO RELEASE**

Figure 20 - Maintenance Programs for New Certification Programs

Repairs for the newer aircraft are required to be damage tolerant. In answer to this requirement, DAC has developed the MD-11 SRM to include repairs that have been analyzed for damage tolerance. The repairs have recommended maintenance programs (inspection program thresholds, repeat intervals, and inspection methods) on each repair drawing. In addition Section 51 of the SRM is being updated to include guidelines for designing damage tolerance rated repairs. Similar activities are in process for the MD-90.

Significant structural service bulletins are a continuing problem that requires diligent effort on the part of the operators, regulators, and the manufacturer to be resolved. DAC has endorsed the Airworthiness Concern (AC) process developed by the ATA as a means to rapidly and accurately assess the significance of pending maintenance actions.

SUMMARY

Aircraft safety is everyone's business. Seldom does an accident result from a single cause or even the combination of two or three seemingly unrelated events. In most accidents resulting from structural failure, the fail-safe margin has been exceeded a number of times in a variety of different ways. From the Air Traffic Controller, to the engineer designing a reliable system, to another engineer designing durable structure,

safety is all important because one depends on the other and vice versa. In recent times safety agendas have been published that attack one or the other root cause issue based solely on frequency of occurrence. Unfortunately, the truth is that no cause is more important than any other when safety is concerned. What has been done for structural integrity of our civil aircraft fleet has been reviewed. The industry has come a long way in the past seven years and must continue the effort, this effort, and every other safety related endeavor.

ACKNOWLEDGMENTS

The author wishes to acknowledge Joan Hughson, Anthony Lombardi, and Roger Skinner whose efforts were invaluable in helping to write and critique this paper.

COMMUTER AIRPLANE STRUCTURAL DESIGN AIRWORTHINESS

Robert B. Held
Cessna Aircraft Company

ABSTRACT

There has been a renewed thrust, starting in 1989, on Continued Airworthiness of Commuter Airplanes. This paper presents a summary of some of the activities that have happened in the areas of continued airworthiness of the aging commuter fleet, and the structural design requirements. For the aging commuter fleet, major emphasis has been in the general areas of service bulletins, structural inspections, airplane maintenance, and criteria for continued operation of aging airplanes. For new commuter airframe designs, new rules have been issued and other rules amended. The thrust is to require damage tolerance structure for all new commuter airplane designs.

CURRENT COMMUTER AIRPLANES

The current thrust of reviewing the commuter fleet condition and developing and implementing plans to ensure continued airframe airworthiness started in 1989. In March 1989, the General Aviation Manufacturers Association (GAMA) organized a corrosion conference that was held in St. Louis, Mo. In April 1989, in Kansas City, GAMA and the Regional Airline Association (RAA) co-hosted an International Conference on Aging Commuter Aircraft. The basic mission was for the manufacturers, operators, and the regulators to review and discuss the aspects of the commuter airplane fleet. The major focus was on corrosion, fatigue, service information, inspections (including nondestructive testing), maintenance, repairs, communication, human factors, and supplemental inspection documents.

In 1989, when the current thrust started, the Regional Aircarrier Passenger fleet consisted of:

- 1800 airplanes
- 59 different types
- 17 different manufacturers
- 165 different operators

The aircraft to be considered were those with less than 60 passenger seats, in scheduled air carrier service, multi-engine, greater than 6000 pounds maximum weight, that did not have a damage tolerance certification basis, and were not covered by ATA/AIA task force.

These airplanes have certification basis in both Part 23 and Part 25 (or the proceeding applicable regulations) and operate in both Part 121 and Part 135 categories.

Following the GAMA/RAA conference in April 1989, Service Bulletin and Airworthiness Directive (AD) reviews were conducted to determine if additional AD action was required on mandatory service bulletins and if closing action was needed on existing AD's. This review covered both systems and airframes. These reviews proved to be very productive in that it provided an opportunity for the three major segments of the commuter industry - Manufacturers, Operators and Regulators - to develop action plans to enhance safety. The FAA also did on-site maintenance evaluations of selected commuter operators.

Since early 1989, the commuter airplane manufacturers, the operators and the regulators have "plowed a lot of ground," some of it several times, with the focus on developing programs to ensure the continued airworthiness of commuter airplanes.

Although there is continued focus on the operation and maintenance aspects of the Commuter Continued Airworthiness Program, the focus here will be on the airframe structural integrity.

The basic challenge in developing a program for the commuter fleet was the type of program needed to maintain the structural integrity of the airframe. Was it airframe life limits? inspections? modifications? or a combination of these?

Life Limits - How is a life established, accumulated fatigue damage or crack growth? How are time limits for airframe inspections established? There were a number of presentations on the design, operation, and maintenance of commuter airplanes made to GAMA members, RAA operators, FAA and other regulator agency personnel, and members of the Technical Oversight Group for Aging Aircraft (TOGAA). During these presentations, the manufacturers reviewed design concepts, airframe substantiation for certification, and inspection programs. As might be

expected, in this category of airplanes there is considerable variation in design concepts, substantiation, and certification data. The airframes cover small airframes certified, for the most part, by static testing only to some of the larger airframes that have been substantiated to Damage Tolerance Criteria.

How has the structural integrity of the smaller commuter airframes been maintained to date? Prime factors are conservative design loads, low normal operating stresses, design details, inspections, modifications, and good maintenance practices. So, what is the concern? The concern is how long we can continue to operate the aging commuter fleet using the current inspection, part replacement, and maintenance programs. As the discussions continued on the format for the Commuter Structural Integrity Program, the operators, manufacturers, and regulators continued to review their aspects of the program to discern opportunity for improvement.

The Aging Aircraft Act of 1991 requires the FAA to enact regulations to address aging airplanes used in air transportation. In 1991, the FAA communicated that it was considering a proposed rule that would require the establishment of operational life limits for each airplane type that was affected by the Aging Commuter Airplane Program. Operation would be restricted to these published lives unless specific FAA approved action was taken. The formal notification of the requirement for operational limits was communicated by FAA Notice 93-14 published in the October 5, 1993, Federal Register.

As a result of the plan to require operational limits, a small transport/commuter airplane working group of international representation was formed and convened in August 1992. The working group members represented manufacturers, operators, and regulators. Two tasks were defined for the working group (WG):

Task 1 - Develop criteria, requirements, and guidance to establish operational limits for airplanes of less than 75,000 pounds maximum certificated takeoff weight, used in scheduled air carrier or commuter service, that were not certificated to damage-

tolerance criteria or did not have approved supplemental inspection programs or equivalent.

Task 2 - Develop criteria, requirements, and guidance necessary to operate beyond the operational limits established under task 1. These may be presented as a rule, an advisory circular, or a combination of them, and may include guidance for supplemental inspection programs.

The working group's mission was to develop an advisory circular (AC) to provide a means of compliance for establishing operational limits (Task 1) and method for extending the operational limit (Task 2). The applicability of the AC was for (a) airplanes of less than 75,000 pounds maximum certified takeoff weight, which are used in scheduled air carrier or commuter service; (b) airplane types not certified to damage tolerance criteria; and (c) airplane types not having an approved supplemental inspection program or equivalent.

The major challenges that continued to surface during the development of the AC were How is the operational limit established? accumulated fatigue damage analyses or crack growth using principles of fracture mechanics? The AC identified three options: 1) Fatigue test and/or analysis, 2) Comparison with similar structure, or 3) Use of a fleet based limit. The preferred option was fatigue analysis using the crack propagation analysis method. Multiple site damage and multiple element damage evaluations were also required in the determination of the operational limit. To extend the operational limit, the AC identified specific actions that included inspections, component replacement, modifications, or a combination of these. Repetitive inspections were to be based on the principles of fracture mechanics or crack growth test results. Since we are dealing with an aging fleet, the most significant part of the evaluation would most likely be the extension of the operational limit.

The Small Transport/Commuter Airworthiness Assurance Working Group (SAAWG) completed a draft of the advisory circular in April 1994. The Aviation Rulemaking Advisory Committee (ARAC) on Transport Airplane/Engine Issues voted to accept Advisory Circular 91-XX in June

1994 and to recommend it's acceptance to the FAA. Neither the Advisory Circular based on AC 91-XX or the rule for establishing operational limits has been issued.

After ARAC recommended draft Advisory Circular 91-XX, the FAA reconsidered the operational limit concept. Contacts with the FAA indicate that operational limits will not be required. The FAA intends to publish a supplemental notice of proposed rulemaking this fall. This supplemental notice is expected to modify the "operational limit rule" published in Notice 93-14 Aging Aircraft Safety (October 5, 1993, 58 FR 51944) to a "supplemental inspection program (SIP) rule." In order to validate the policy material proposed for this SIP rule, the FAA will be contracting, through its National Aging Aircraft Research Program, for damage tolerance assessments and development of Supplemental Inspection Programs (SIP's) on selected commuter airplanes.

There has been a continued assessment of fleet airplane conditions and inspection programs. High-time airplanes and airplanes used in more severe environments have been inspected to monitor fleet airframe conditions and inspection programs. Structural inspection intervals have been revisited based on crack growth rates. Inspections employing NDT techniques have been evaluated in light of some of the latest developments in nondestructive testing for cracks and corrosion. Due to the detail part geometry and materials used in some of the older airframe designs, NDT inspections can create many challenges in crack detectability. For structures that are fatigue critical at fastener locations, removing fasteners and establishing the hole quality can produce increased inspection intervals, provide increased level of safety in airframe structural integrity, and could reduce operator inspection costs. There has been assessment of different techniques in the fleet to improve the quality of the NDT inspections. A segment of a small commuter airplane wing spar has been sent to Sandia National Labs for use in their nondestructive inspection testing (NDT) validation program.

FUTURE COMMUTER AIRPLANES

Looking to the structural integrity of commuter airframes of the future, FAR 23 design rules for commuters have been changed or are proposed. During the development of Joint Aviation

Requirements JAR 23 and the harmonization of FAR 23 and JAR 23, airframe fatigue rules were modified. In JAR 23, inspection requirements were included in Paragraph 23.571 (Pressurized Cabin Structure) and Paragraph 23.572 (Wing, Empennage and Associated Structures). JAR 23.573 was included to require damage tolerance evaluation for composite structures and provide the damage tolerance criteria for metallic airframe structures if this option was chosen by the manufacturer. Paragraphs 23.571 and 23.572 included the option to chose damage tolerance in lieu of the historical approaches of fatigue strength or fail-safe strength.

The FAR 23 rules have been changed and Notice of Proposed Rulemaking No. 94-20 (July 8, 1994, Federal Register, Vol. 59, No. 130) issued. These rules were generated to create harmonization with JAR 23. In the proposed changes, FAR 23.574 was added to require damage tolerance evaluation for metallic airframes of commuter airplanes. There is an existing rule, Damage Tolerance and Fatigue evaluation, for composite airframe structure and includes the option for designing the metallic structures identified in FAR 23.571 and 23.572 to damage tolerance criteria. The proposed changes also include a new paragraph, 23.575, "Inspections and other procedures." The new paragraph requires inspections for airframes designed to FAR Paragraphs:

- 23.571 Pressurized Cabin Structure
- 23.572 Wing, Empennage and Associated Structures
- 23.573 Damage Tolerance and Fatigue Evaluation of Structure
- 23.574 Metallic Damage Tolerance and Fatigue Evaluation of Commuter Category Airplane

These inspections must be included in the limitations section of the Instruction for Continued Airworthiness required by FAR 23.1529.

SUMMARY

The activity since 1989 has provided the opportunity to those involved in designing, manufacturing, operating, and maintaining commuter airplanes to raise their awareness on structural integrity issues. Continued focus on the mission and harmony in the team effort will provide continued structural integrity for the commuter airplanes. Harmonization of the design

rules to provide damage tolerance structure will help ensure airworthiness for new commuter airframe designs.

To resolve issues, whether we see them as problems or opportunities that come to our awareness, and maintain a harmonious team spirit, the words from Albert Einstein may be appropriate, "Problems cannot be solved at the same level of consciousness that created them."

MANAGED OR MANDATED MAINTENANCE PROGRAMS A GROWING CONCERN

Tony McBride
United Parcel Service
Louisville, KY

The Federal Aviation Administration (FAA) has long recognized the application of reliability methods as an integral part of the management of approved aircraft maintenance programs. Through cooperative efforts by operators, the FAA, and manufacturers the industry has continually improved both aircraft design criteria and methods for the development and monitoring of aircraft maintenance programs.

Examples of these improvements include improved design criteria (FAR 25.571 Damage Tolerance), supplemented by maintenance and inspection activities to detect environmental, accidental, and fatigue damage (MSG-3) Maintenance Steering Group Document-Revision 3. The objective of these improvements continues to support the industry goals for safety and cost-effective operations. In the past few years the FAA has taken a position of mandating maintenance activities through the Airworthiness Directive (AD) process.

Although the AD process is effective for addressing immediate safety concerns, it should not be used to mandate routine maintenance requirements. ADs of this nature have imposed significant and unwarranted burdens on operators by increasing administrative tasks and limiting compliance alternatives. These "global" solutions often conflict with the vastly different operating plans across operators and reduce the ability of the operators to manage their maintenance program through the use of reliability methods.

The purpose of this paper is to highlight the need for a more effective process for evaluating safety concerns which may be addressed through the maintenance and inspection program and thus preclude the abuse of ADs.

The information I am about to present will serve to illustrate the correlation between the growing number of ADs and the resultant loss of control by the operators to manage the maintenance on the aircraft they operate. Although this report focuses on the maintenance of aircraft structure, a

similar trend exists for non-structural components and systems as well. I would also like to point out that this report reflects only two of the four aircraft types we at UPS currently operate, the 727 and 747, but are representative of other aircraft subject to the aging aircraft mandates and Airworthiness Directives.

I now would like to point out the growing trend of ADs which require repetitive maintenance actions applicable to structure and corrosion.

First we will look at the 727 fleet. As you can vividly see in Figure 1, there has been a significant upturn in the issuance of ADs subsequent to the Aloha accident, which occurred in April of 1988. Since that point in time, the number of ADs has risen from 9 to 47 in 1994. This represents a 522% increase. With each of these ADs comes the significant burden of tracking and reporting, special work documents, mandatory accomplishment dates as well as many other administrative tasks.

In Figure 2 you see the 747 aircraft and an identical growth trend, where ADs increased from 16 in 1988 to 67 in 1994 or a 419% increase. We see this trend as a threat to the success of our operations as they influence our ability to remain compliant and profitable.

As we all know, there is a cost associated with everything. What I will share with you next are several charts that will provide an example of the cost of compliance for these AD's.

Keep in mind that the numbers in these charts reflect only the cost of the maintenance action and do not include the associated costs derived from administration and record keeping or materials.

The totals on these graphs represent the percentage of labor hours for routine or managed tasks and those mandated by an AD that are required to maintain the aircraft during one 72 month "D" check cycle. Again these are derived from only the UPS operation and should represent a typical impact to each individual operator.

The first graph (Figure 3) shows routine Maintenance Totaling 36,977 Labor hours or 50.4% of the total labor hours.

The remaining labor hours are attributed to ADs:

CPCP	26,646 Hrs	36.3%
SSID	675 Hrs	.90%
Other	9,074 Hrs	12.4%
Total	**36,395 AD Hrs**	**49.6%**

As you can see in Figure 4, an identical trend is shown for the 747 fleet with routine maintenance totaling 26,279 labor hours or 47.1%. Again, the remaining labor hours are attributed to ADs.

CPCP	12,169 Hrs	21.8%
SSID	5,465 Hrs	9.8%
Other	11,897 Hrs	21.3%
Total	29,531 AD Hrs	52.9%

This trend is confirmed by combining the two charts as shown in Figure 5. The combined labor cost for ADs done on these two aircraft types during a single "D" check cycle totals just under 3 million dollars (65,926 Labor Hours x $45 Labor Cost per Hour).

As the number of mandated tasks grows, the operator loses the ability to effectively manage the maintenance of the aircraft. Most importantly we lose flexibility. Sure it could be argued that alternate means of compliance can be obtained, but this process only adds another degree of complication to our effort. Aside from the loss of flexibility, these ADs often duplicate or overlap existing maintenance requirements. I have an example illustrating this fact.

AD 93-08-12 (Table 1) was published to inspect for cracks in the fuselage internal structure listed in Service Bulletin (S/B) 747-53-2349. The inspection was required on certain floor beams, frames, door cut-outs, and bulkheads between B.S. 520-1100.

Table 1 - AD 93-08-12.

93-08-12 BOEING: Amendment 39-8559. Docket 92-NM-36-AD.

Applicability: Model 747 series airplanes; as listed in Boeing Service Bulletin 747-53-2349, dated June 27, 1991; certificated in any category.

Compliance: Required as indicated, unless accomplished previously.

To prevent loss of the structural integrity of the fuselage, accomplish the following:

(a) Prior to the accumulation of 22,000 total flight cycles, or within 1,000 flight cycles after the effective date of this AD, whichever occurs later, unless previously accomplished within the last 2,000 flight cycles; and thereafter at intervals not to exceed 3,000 flight cycles: Perform a detailed visual internal inspection to detect cracks in the areas of the fuselage internal structure listed below, in accordance with Boeing Service Bulletin 747-53-2349, dated June 27, 1991; and prior to further flight, repair any cracks detected, in accordance with FAA - approved procedures.

(1) Section 41 and 42 upper deck floor beams.
(2) Section 42 upper lobe frames.
(3) Section 46 lower lobe frames.
(4) Section 42 lower lobe frames.
(5) Main entry door cutouts.
(6) Section 41 body station 260, 340, and 400 bulkheads.
(7) Main entry doors.

A typical section of the fuselage being inspected by the S/B is shown in Figure 6. These areas of the fuselage are now being inspected by the Corrosion Prevention and Control Program (CPCP) AD, the Supplemental Structural Inspection (SSI) AD, the Maintenance Planning Data Document (MPD) Structural Inspection (SI) in addition to the 93-08-12 AD These may be different levels of inspection and different time intervals. However, the same piece of structure will be reviewed 3 or 4 times to maintain structural integrity under the guise of safety. In fact, the operator will integrate the overlapping inspections whenever possible into one program and then try to administer the paperwork to ensure he meets the intent of the law, and hope he doesn't stumble into a paper trap.

To enable the industry to meet the growing concerns of how aircraft are used and maintained the FAA, manufacturers, and operators have worked together to revise regulations for aircraft design and to improve maintenance program decision logic. These changes include FAR 25.571, which

requires the manufacturer to be even more responsible for potential environmental, accidental, and fatigue damage during initial design.

In fact, most aircraft certificated after 1980 have been fatigue tested to twice the design cycle life. This has been done at great expense to the manufacturers and the airlines purchasing new aircraft. This demonstrates a willingness to make warranted improvements and justifies the additional expense by increasing safety and reliability over the operational life of the aircraft.

The enhancement of the Maintenance Steering Group Document (MSG-3) was based on the history of the reliability data gained by the industry and has been revised to support the changes in design criteria and to address safety concerns. These improvements were done again with safety in mind and have been accepted as meeting those goals from a regulatory perspective. These steps were taken not only to improve safety, but to help operators be in a position to maintain aircraft in a routine business environment, reduce unscheduled maintenance, and allow the reliability program to function as it has over the past 30 years.

One example of an attempt to preclude the publication of an AD, by including the information in the Maintenance Program, revolves around the 757/767 Supplemental Structural Inspection. These aircraft were certified to the latest change to FAR 25.571 and MSG-3 logic pertaining to fatigue damage. At the time of certification there was a documented understanding and agreement between the FAA, manufacturer, and airlines to finalize the SSI thresholds and inspection procedures at a later date.

As noted in the 757 Maintenance Planning Data Document (MPD) in Figure 7, the reassessment would be completed by December 1992. The threshold for implementation of the Supplemental Inspection Program (SIP) would not exceed December 1997.

The 757 Maintenance Review Board Document (MRB) in Figure 8, was specific in stating structural inspections arising from certification activities are specified in section 9 of the MPD. The tasks are required of each operator of the 757.

There was similar language for the 767 documents. Now, without any specific airworthiness concern with either aircraft, the FAA is contemplating issuing an AD mandating these inspections. While one legal interpretation of the law may require the need for an AD, it seems rather unnecessary to this operator. In one respect, it actually undermines the integrity of the people in the organizations present at the time of the certification process for those aircraft. If, however, it is determined that an AD is the only way to legally approve the SSI for the 757 and 767 fleets, then it is recommended the AD allow the operators to manage the program under the normal reliability process as originally intended.

The principles of how the FAA decides to govern the airlines on Maintenance Programs is provided in the FARs. As conditions change and we, the industry, become more intelligent on the ways to operate and maintain aircraft, FARs can be changed or added upon. A good example of this process are the proposals to institute FARs for CPCP and Repair Assessment. As proposed, the CPCP will become part of the Maintenance Program with oversight by the Principle Maintenance Inspector (PMI) and managed by the airline Reliability Program. MSG-3 logic has been improved to meet the intent of the proposal and meet the safety concerns for the future. The Repair Assessment will change the Structural Repair Manuals and provide guidelines to reinspect repairs as required to meet new Damage Tolerant Requirements. This provides an orderly step to improve the quality of maintaining aircraft without the costs associated with ADs.

I would like to propose an example of how an AD can be written to help airlines manage an item after the initial airworthiness concern is abated. The AD used in this example is 90-17-19 which was developed to address an airworthiness concern on 747 Flap carriage spindles (shown in Figure 9). As shown in Figure 10, the AD spelled out the immediate actions required by the operator to overhaul these components within the specified thresholds. However the AD also mandated a recurring overhaul interval (Shown in the bold text in Section B.2), thus perpetuating the life of the AD indefinitely. It is with this element of the AD to which we take exception. We feel that closure of this AD could be facilitated by a simple change to the language used in this case. This is illustrated in Figure 11.

The statement could be revised as shown in Figure 11 to require the operator to include the flap carriage spindle as a time controlled item in the maintenance manual for overhaul at 8 years or 30,000 hours whichever occurs first. This requirement would be coordinated through the local PMI and serve as terminating action for the AD.

I am hopeful that this presentation has highlighted our concerns and provided you with a glimpse of the operator's perspective. I strongly believe that a satisfactory alternative can be reached that meets the collective goal for the continued airworthiness of the world's aircraft fleet.

Every morning when we get out of bed, we run the risk of having an accident. Even if we adopt a hermit's life style, we are more likely to meet an untimely end in the so-called "safety" of our own homes than if we travel by commercial jet transport. As you can see in Figure 12, in 1991, the number one cause of accidental deaths in the U.S. were motor vehicle accidents. Falls and accidental poisoning follow. Progressing down the list, you can see some of the other more prominent causes for accidental death are drowning, fire/burns, and suffocation. The last numbers gets to the bottom line. In the U.S., it is significantly safer to take a commercial jet flight than to ride on or be in the physical proximity of an animal drawn cart or vehicle. Think about that. Your death is more likely to occur while taking a romantic carriage ride than if you take a flight from Buffalo to Seattle. It's true that aircraft crashes are very dramatic, but these statistics reflect the fact that they just don't happen very often. There isn't any way to guarantee that an accident won't occur. All we can do is take the precautions which help to minimize that risk, and that's exactly what we're doing. Today, air travel is one of the safest modes of transportation available, and we're committed to keeping it that way.

References

Reference Item	AD Number	Docket Number	Date
AD	93-08-12	92-NM-36-AD	06/27/91
AD	90-17-19	89-NM-120-AD	09/21/90
727 CPCP	90-25-03	89-NM-268-AD	07/28/89
727 SSID	84-21-05	34-4920	11/01/84
747 CPCP	90-25-05	89-NM-271-AD	07/28/89
747 SSID	84-21-02	89-NM-159-AD	02/12/90
FAA AD Index	N/A	N/A	01/95

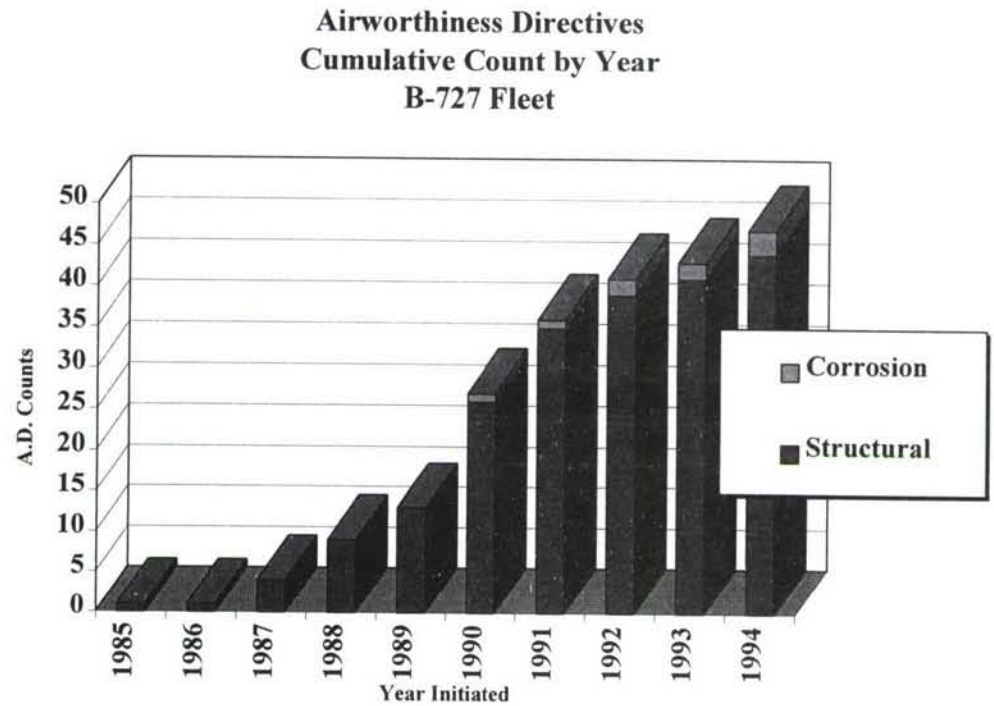

Figure 1 - Airworthiness Directives Cumulative Count by Year B-727 Fleet.

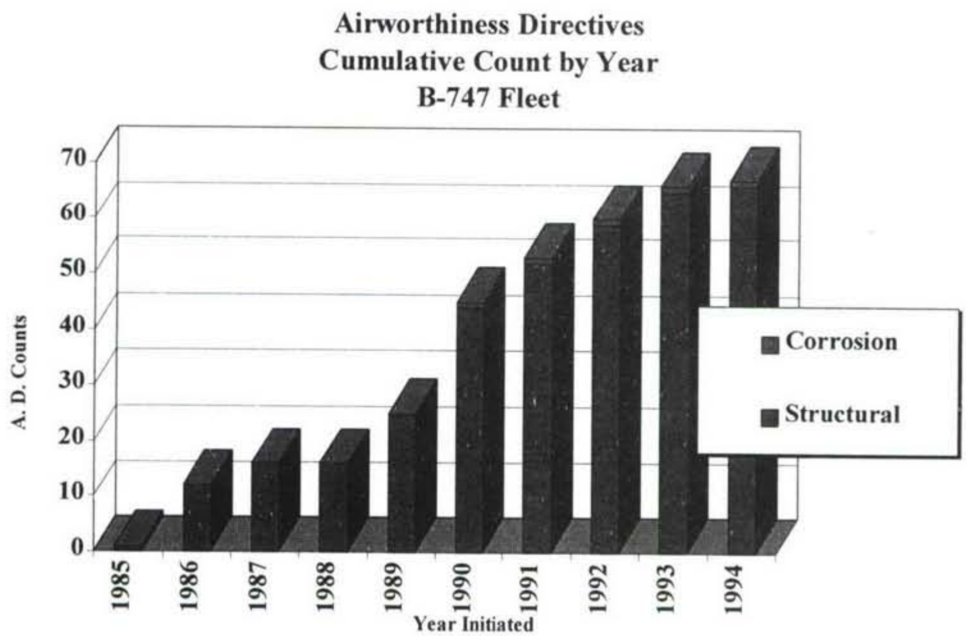

Figure 2 - Airworthiness Directives Cumulative Count by Year B-747 Fleet.

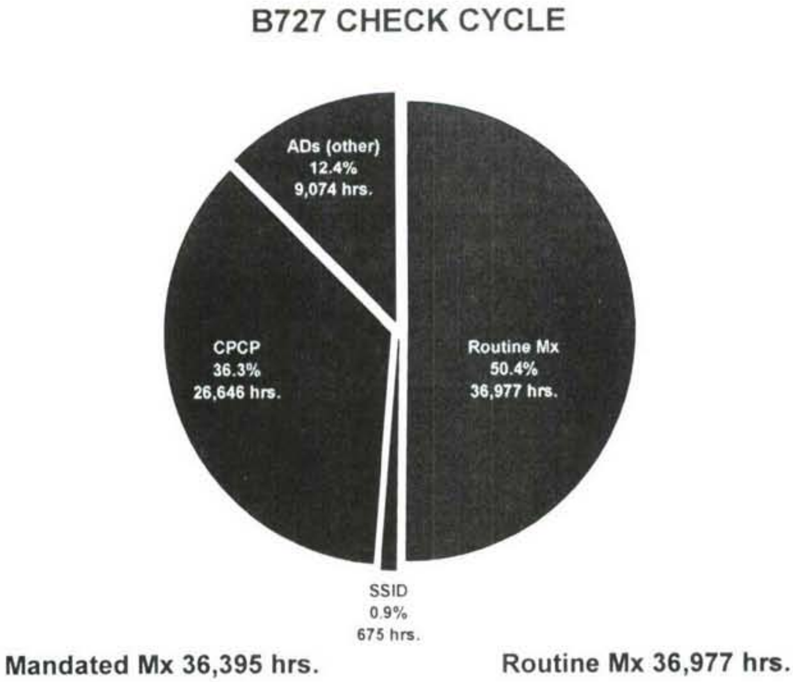

Figure 3 - B-727 Check Cycle

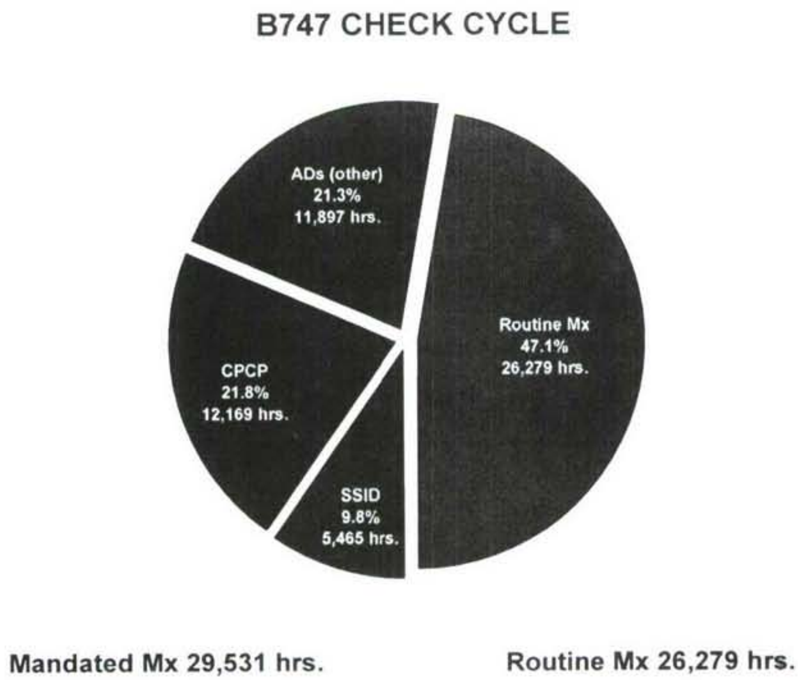

Figure 4 - B-747 Check Cycle

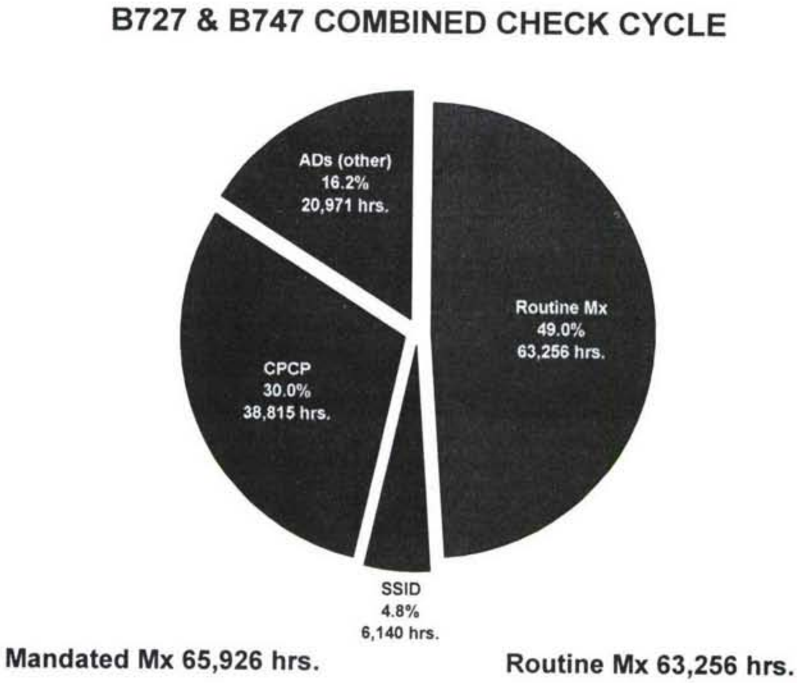

Figure 5 - B-727 and B-747 Combined Check Cycles

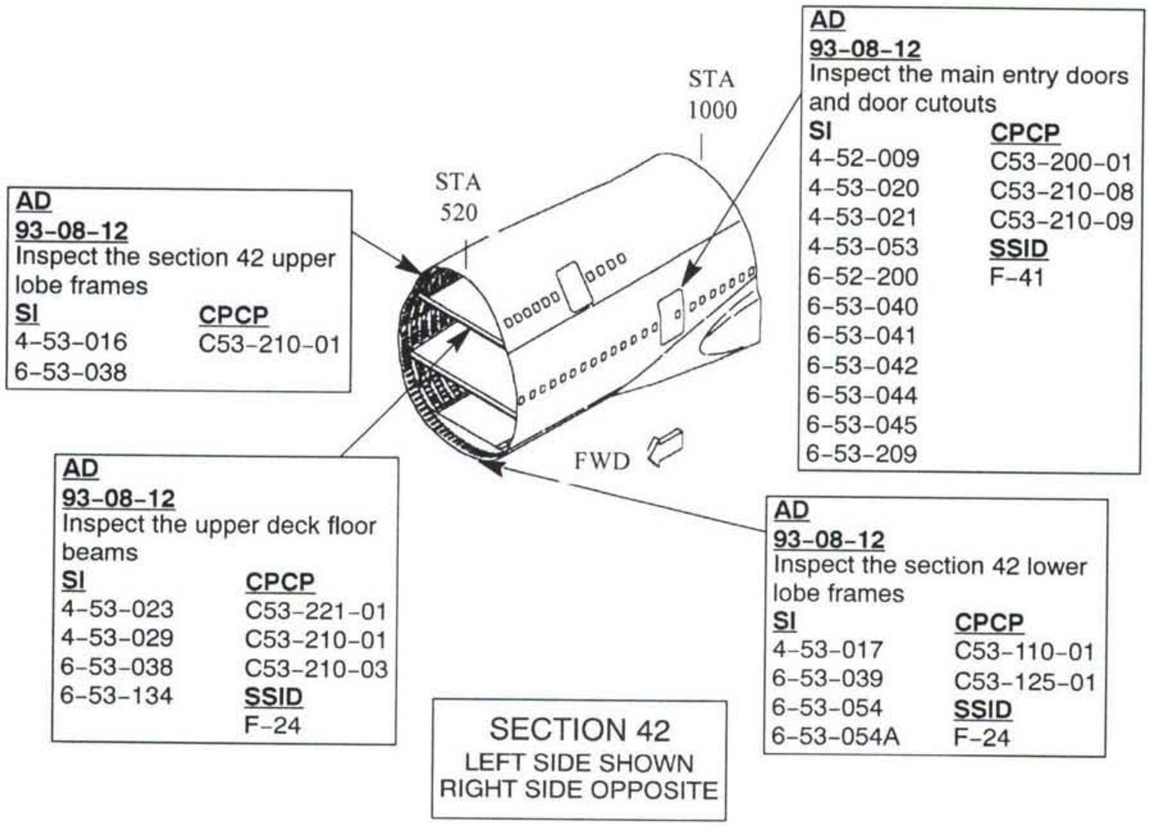

Figure 6 - Typical Section of Fuselage Inspected by Service Bulletin 747-53-2349

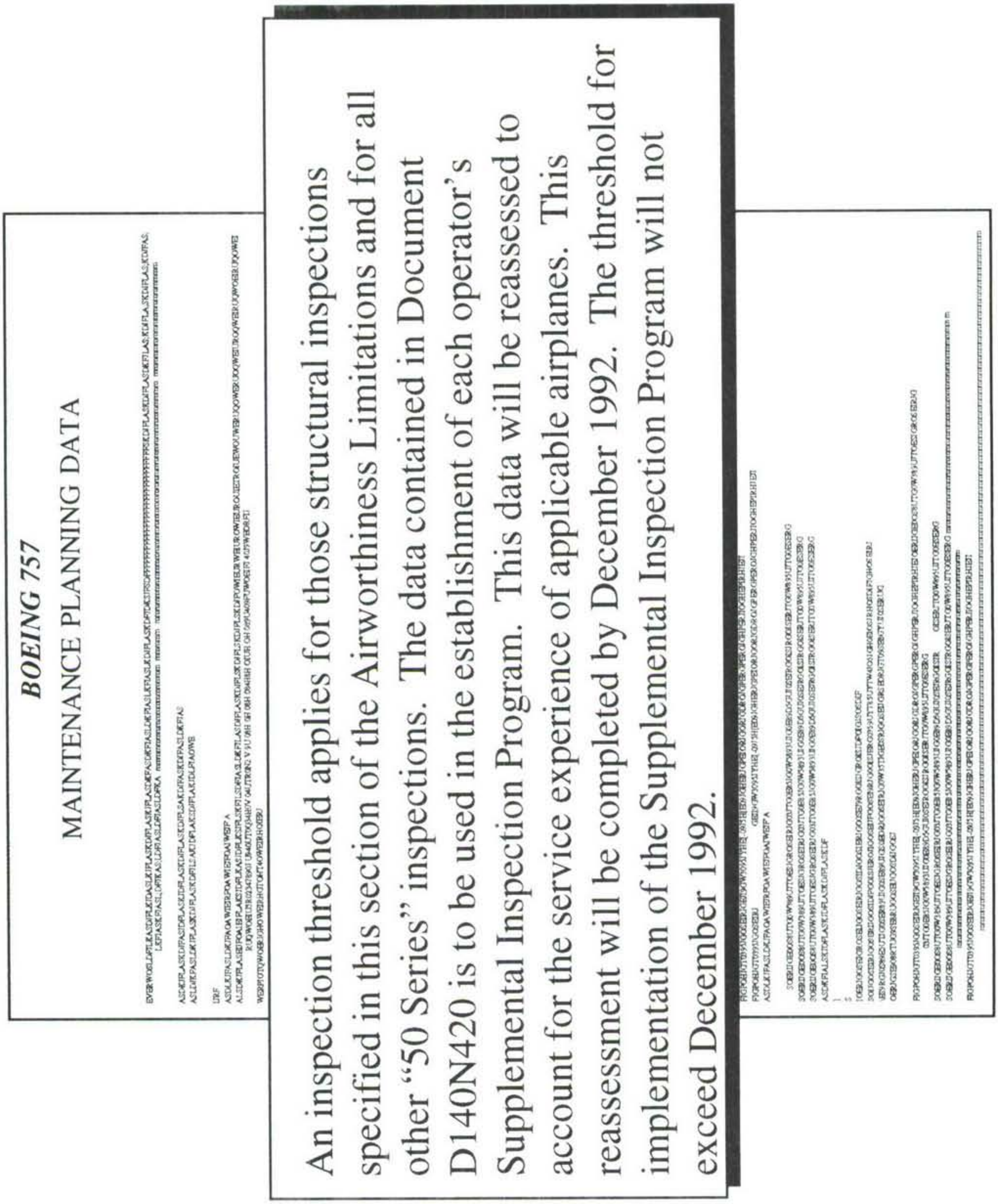

Figure 7 - 757 Maintenance Planning Data Document (MPD)

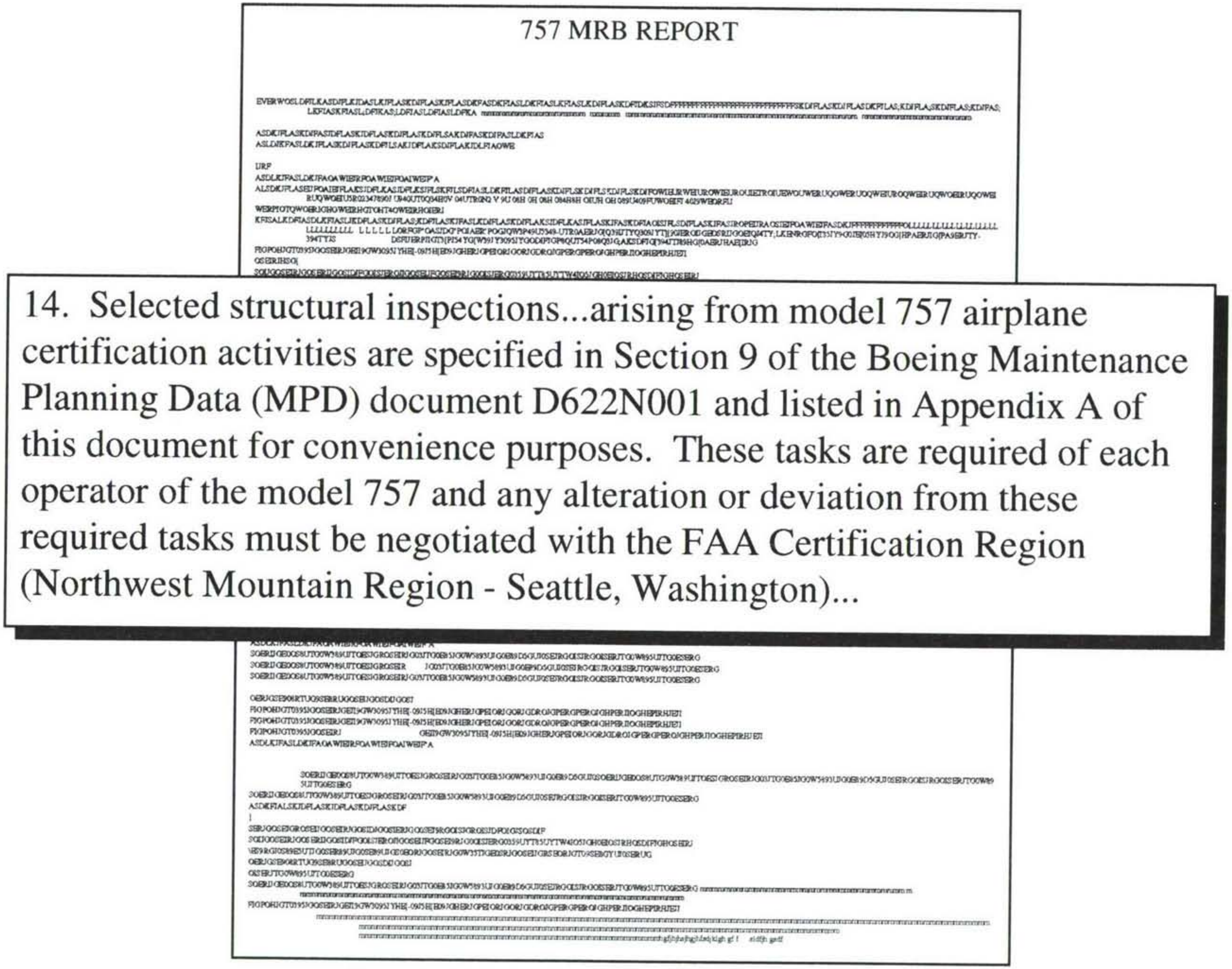

Figure 8 - 757 Maintenance Review Board (MRB) Report

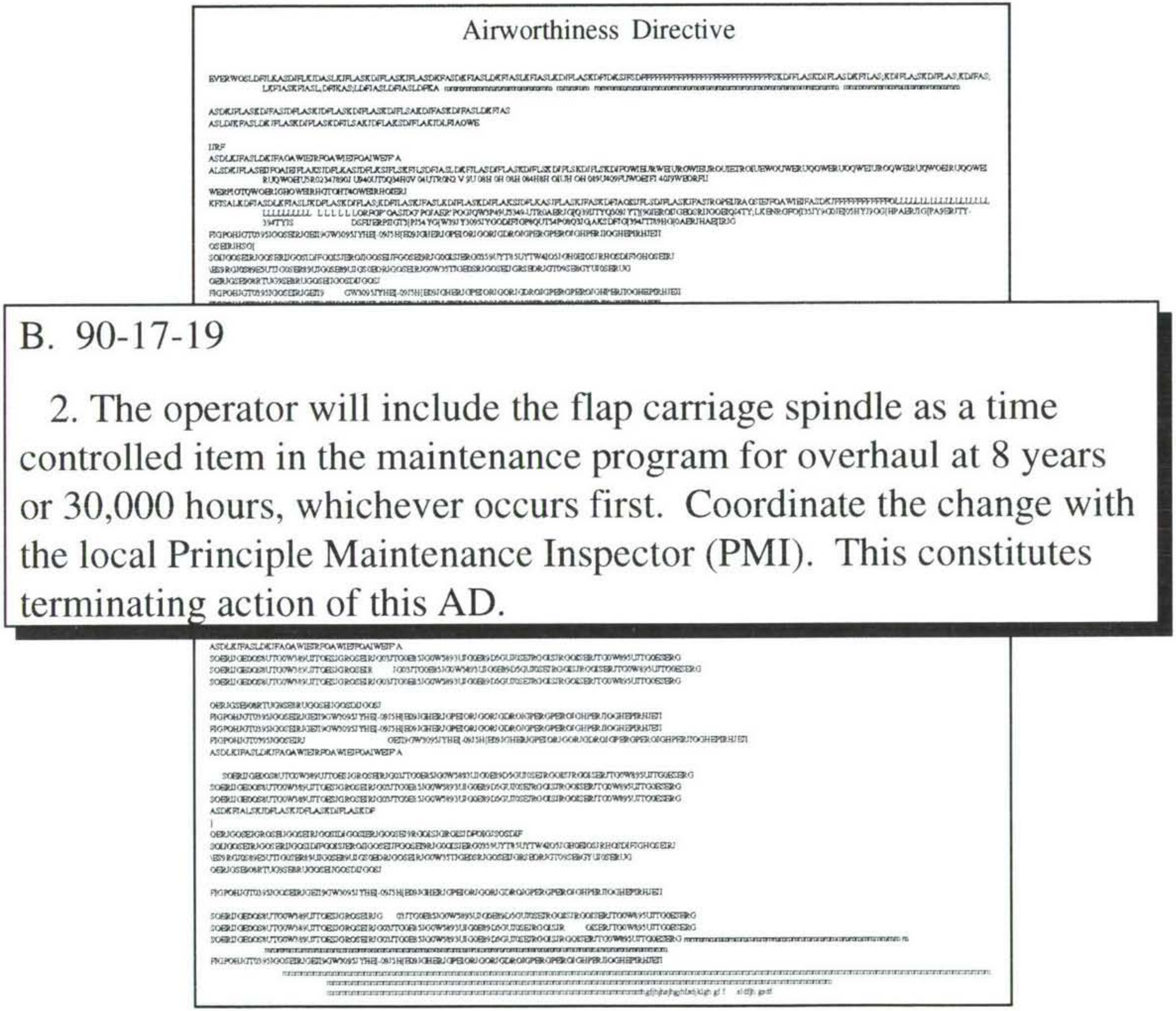

Figure 9 - Airworthiness Directive 90-17-19

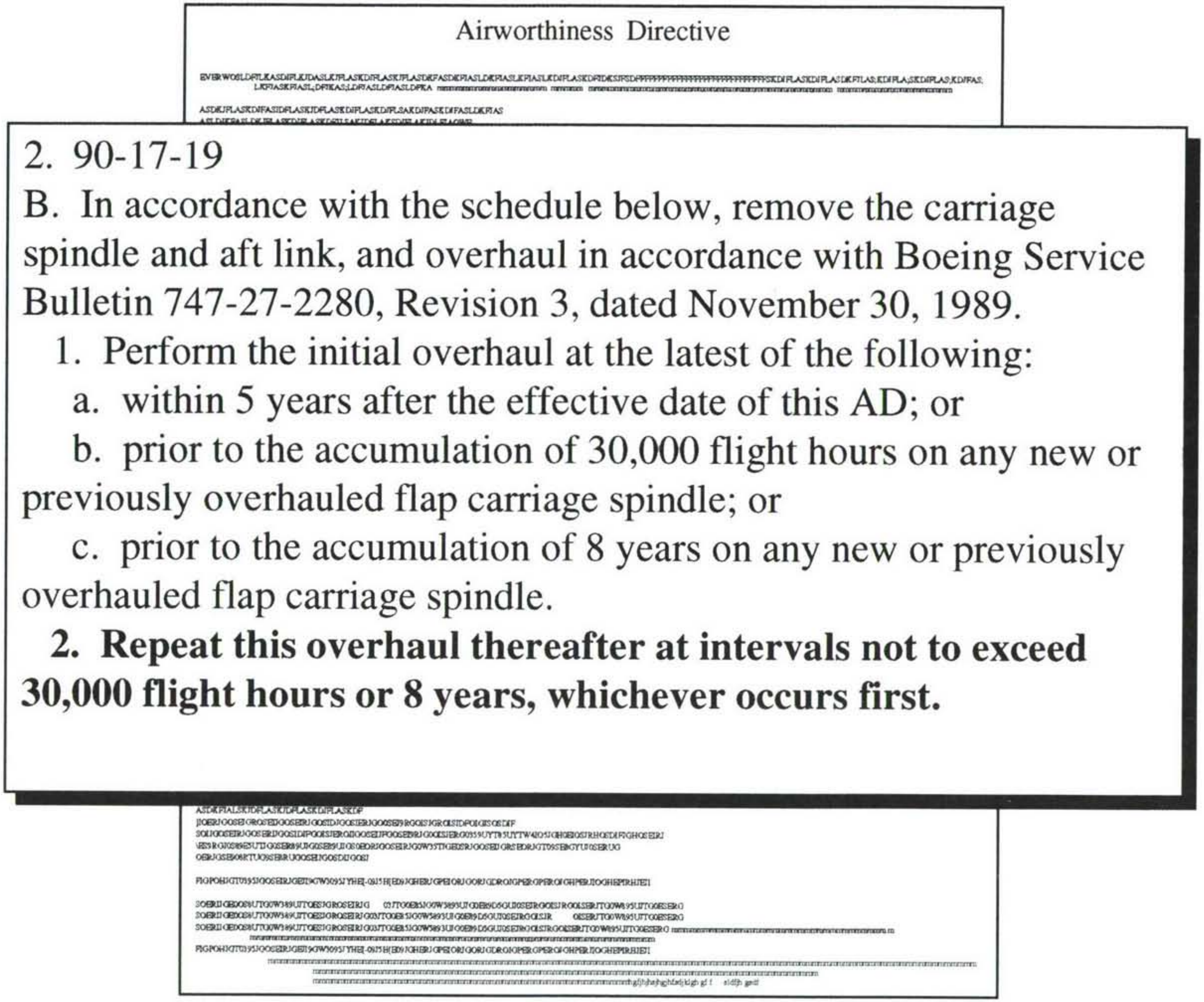

Figure 10 - Mandated Reoccuring Overhaul Interval

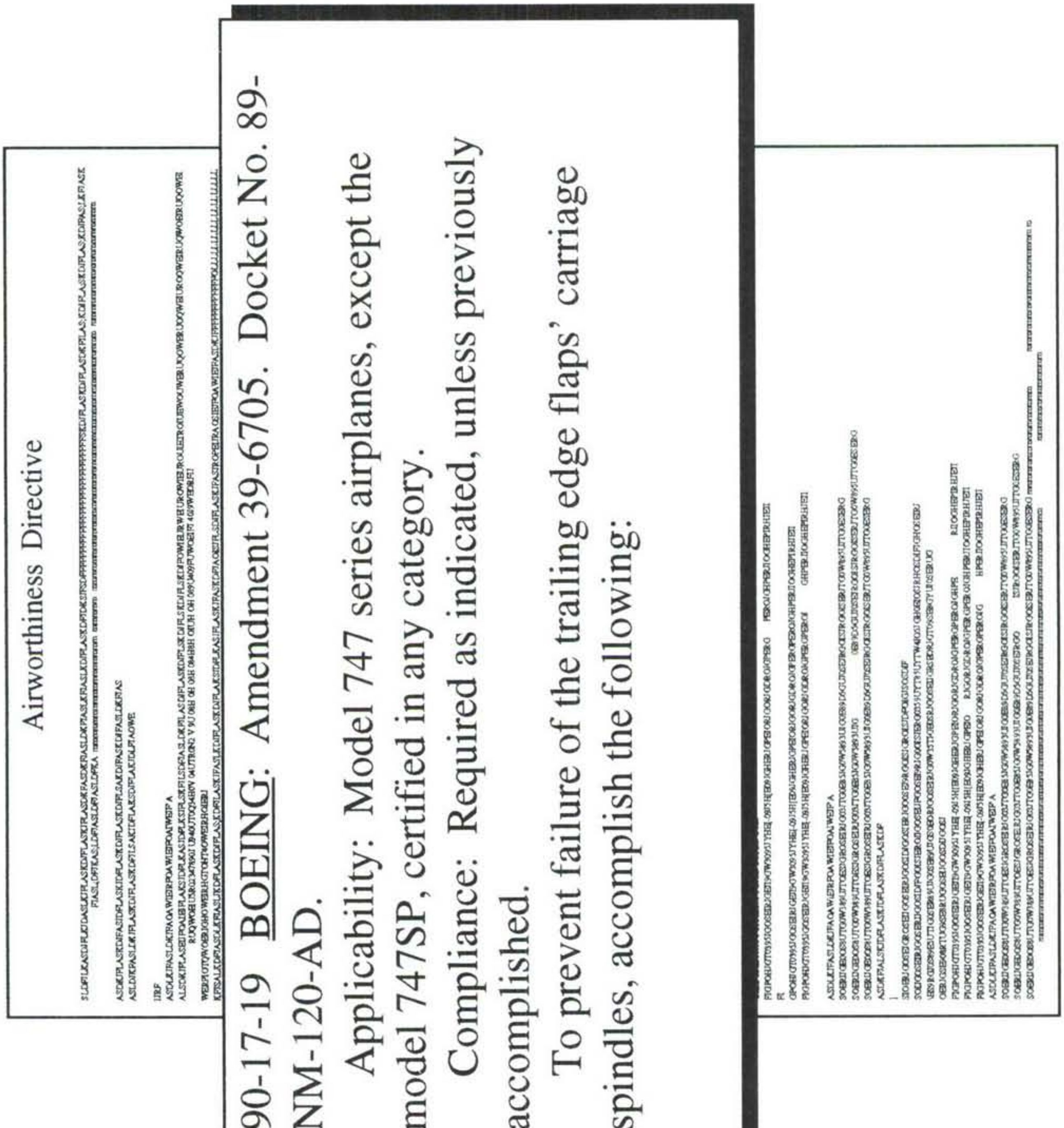

Figure 11 - Suggested Revision for AD

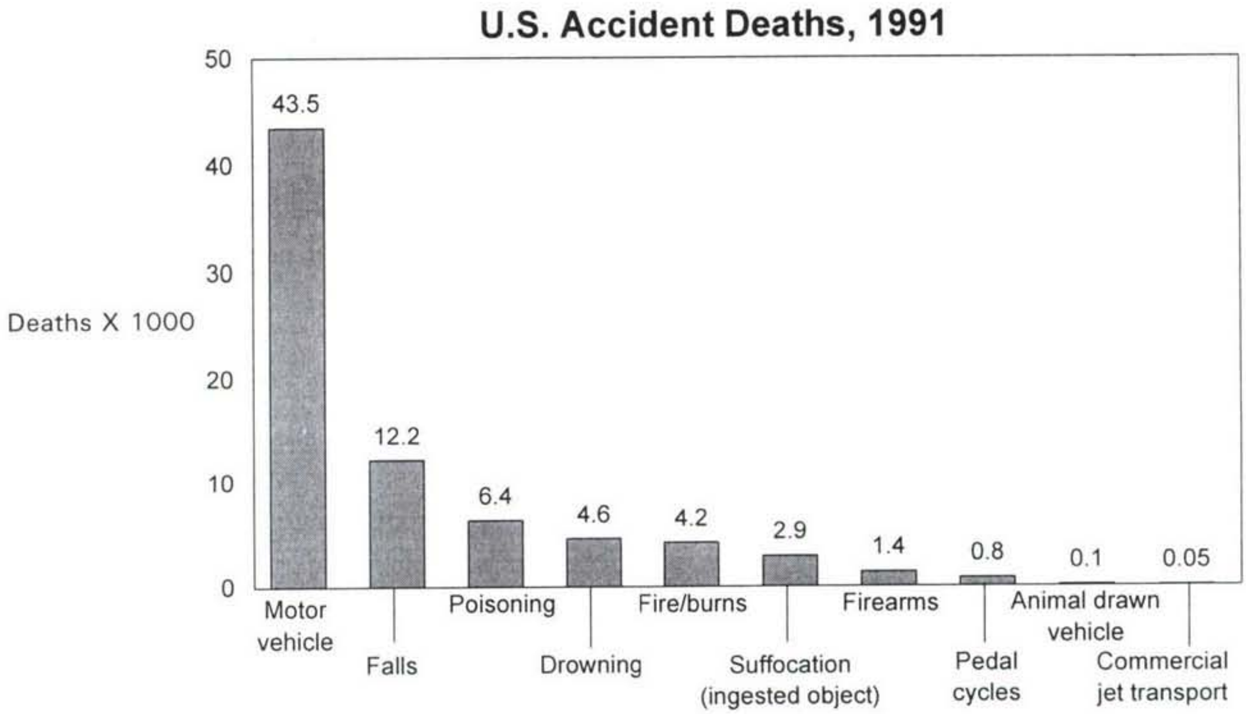

Figure 12 - Accidental Deaths in the United States, 1991

MODIFICATION STATUS OF THE OLDER 747 JT9D-POWERED AIRPLANES

Robert D. Vannoy
Boeing Commercial Airplane Group

SUMMARY

This report provides information on the modification status of the older Boeing 747 airplanes. Major maintenance requirements and timelines for these airplanes have been established by mandatory structural modifications including the modifications to the fuselage nose section (section 41) and the recently identified engine strut modifications. Ownership changes, the status of active and inactive airplanes, and operator plans that have been conveyed to Boeing are reviewed. Retirement trends and considerations show that many of the older 747 airplanes will be retired before modifications take place. Based on the trends and outlook presented here, there is adequate capacity in the industry to complete the required modifications.

INTRODUCTION

This report will focus on the older Boeing 747 airplanes; those delivered in the 1970's. The 747 entered service twenty-five years ago this year, and it is appropriate to review significant changes in ownership, how the older airplanes are utilized today, and the impact that the aging airplane programs have had.

The 747 literally "changed the world" and continues to provide the majority of lift today in the large airplane category. Many of the earliest 747 airplanes are still in active service and an obvious question is "How long will these older airplanes last?" To gain insight into the answer to this question the following topics are addressed:

1. Airplane production from 1970 to 1979
2. Ownership changes
3. Status of active and inactive airplanes
4. Major mandatory modifications
    - Section 41 (fuselage nose section) modifications
    - Nacelle strut modifications

The discussion will focus on 747 airplanes powered by Pratt and Whitney JT9D series engines (excluding JT9D-70). This group is important because of the strut modification requirements to be discussed later.

747 PRODUCTION

During the first ten years of 747/JT9D production, about sixty percent were manufactured in the first three years (1970 through 1972). These first 200 airplanes consisted of 747-100 and 747-200 models, mostly in passenger and freighter configurations, and are now at or near 25 years old. The majority of airplanes built from 1970 through 1979 were powered by Pratt and Whitney JT9D engines. This group of 342 airplanes powered by JT9D engines between 15 and 25 years old have the earliest compliance threshold (February 1998) under the strut modification program.

OPERATIONAL STATUS

JT9D-Powered Airplanes Built Before November 3, 1979

Not all of the group of older JT9D-powered airplanes are still operating. The following summarizes attrition from this group.

- Hull losses - 16 airplanes
- Dismantled or otherwise permanently removed from service - 29 airplanes
- No current status (some middle east operators) - 22 airplanes

There are 73 airplanes that show little or no utilization between January and April, 1995. However, 16 of these are scheduled for strut modification. It is assumed that these 16 airplanes will continue to be operated so that only the remaining 57 airplanes are categorized as inactive. Subtracting these 57 airplanes and the airplanes out of service as listed above leaves 218 of the original 342 in the "active" category.

OWNERSHIP STATUS

The group of 342 older JT9D-powered airplanes were initially delivered to 46 operators. Most of these operators (30) still operate 747 airplanes. There are 24 of the original 46 operators that still operate 132 of the original 342 airplanes. The 132 airplanes that are still with the original operator have been subject to relatively consistent maintenance practices. About 100 of the older JT9D-powered airplanes are operated by second tier operators, with 30 additional airplanes are being operated by newer second tier operators (i.e., those established since 1990). These new operators are faced with understanding and implementing the comprehensive maintenance and modification programs that have been established to safely operate the older airplanes.

MANDATORY MODIFICATIONS

As a result of industry concern over the airworthiness of aging fleets the Airworthiness Assurance Working Group (AAWG) formed the Structures Task Group (STG) in 1988. As a result of STG reviews, 31 service bulletins were selected as candidates for mandatory modification. Airworthiness Directive 90-6-06 mandated the initial 31 bulletins. Since the initial review the STG has met regularly to review new developments and bulletins for possible mandatory incorporation; two bulletins have been added since 1989. Most of the initial 31 bulletins have thresholds at 20,000 flights (23 bulletins). Two bulletins have a threshold of 20 years, 5 bulletins were to be incorporated at next overhaul and 1 bulletin had April 1995 as a compliance date. The section 41 service bulletin was part of this initial group and has a threshold of 20,000 full pressure cycles.

As a result of improvements in designs and production that came from service experience and fuselage fatigue testing, the majority of man-hours expended for mandatory modifications apply to earlier airplanes. Line numbers 1 through 200 require an average of approximately 36,000 man-hours per airplane to complete all mandatory modifications, but by line number 450 this number had dropped to less than 25,000 man-hours.

Section 41 (Fuselage Nose Section) Modifications

Currently about 150 airplanes out of 685 affected have had the mandatory section 41 service bulletins incorporated. Out of the 218 active JT9D airplanes mentioned above, 93 have had section 41 modifications completed, leaving 125 unmodified airplanes in the group of older JT9D-powered airplanes.

Taking into account future attrition, we estimate that all remaining active airplanes affected by the section 41 modifications could be complete by year 2005 if modified at a rate of approximately 24 airplanes per year. This rate is consistent with the current average. There is a slight increase over time of airplanes that will reach the incorporation threshold each year based on current utilization. From year to year the number of airplanes to reach the threshold is consistent with no sharp peaks that could put a strain on the industry capacity to perform the modifications.

Nacelle Strut (Pylon) Modifications

In 1994, the nacelle strut modification service bulletins were released after a development program that included three working group meetings and three operator meetings. The strut modifications include improvements to increase the durability of existing structure and some additional structure added for redundant load paths.

One group of airplanes that is of particular interest is the earliest airplanes powered by JT9D engines. The JT9D-powered airplanes built before November 3, 1979 (over 15 years old as of the service bulletin release date) have the shortest threshold for incorporation. Airplanes in this group must be modified by February 1998, 32 months from the effective date of AD 95-10-16. The strut modifications to this group are also the most extensive (8892 man-hours) when compared to modifications of other airplane groups. These factors, when combined with the fact that these are the oldest airplanes in the 747 fleet, lead to the possibility that many of these airplanes could be retired before the section 41 and strut modifications are incorporated.

When we review the trends for all airplanes affected by the strut modification, a rate of about 9.5 airplanes per month would allow for completion by the end of 2001. The current rate of completion and the schedules through 1996 closely match this average rate. More than half of the affected airplanes in service have been scheduled for the modification. Schedules have been provided to Boeing as much as six years in advance, indicating that operators are planning well ahead. When we review the same data for the group of older JT9D-powered airplanes though, the schedules provided to us and the current rate of modifications indicates that many airplanes may not be modified and therefore would be retired or possibly stored for modification at a future date. Of the 218 active airplanes in this group, only about 90 have been scheduled for modification by February 1998, leaving about 130 airplanes that would be left without modifications by the mandatory date. While the threshold can be extended to February 2000 by incorporating some modifications, few operators are considering this option.

When we look closer at statistics for the group of older JT9D-powered airplanes, other trends indicate impending retirement. As could be expected the oldest airplanes in this group have the highest number of flight cycles, more than one-third have more than 18,000 flight cycles, with another 30 to 40 percent over 15,000 cycles. Most of the airplanes with more than 15,000 cycles are 747-100s. We also see that most of this group have not had the mandatory section 41 modifications completed and about one third are currently not active (little or no utilization between January and April 1995).

Projected Maintenance Downtime - Section 41 and Strut Modifications

Based on the projected rates for completion of the section 41 and strut modifications, there will be approximately 11 airplanes in work at all times between now and 2001 for either section 41 or strut modifications. For the 747 fleet, the impact of these two modifications combined will be approximately 4000 days of maintenance down time per year. The strut mod will require about 75 percent of the total airplane days of downtime. Airlines are generally incorporating both modifications during scheduled downtime (D-checks).

CONCLUSION

We have seen that while ownership and operating trends change as the airplanes age, structural modifications are reviewed and mandated as needed to keep the aging 747 fleet flying safely. These major modifications will be a significant factor in the decision to retire many of the older 747 airplanes. It is likely that over 100 of the older JT9D-powered airplanes will be retired between now and the year 2000.

At the current modification rates, and projected future rates, there is sufficient industry capacity to incorporate the necessary section 41 and strut modifications on the 747 fleet.

BOEING STRUCTURAL DESIGN TECHNOLOGY IMPROVEMENTS

S. Rao Varanasi and Jack F. McGuire
Boeing Commercial Airplane Group
Seattle, Washington

ABSTRACT

The paper presents a broad overview of the Boeing aircraft structural improvements in both design and technology, to ensure that continued airworthiness of airplanes is maintained with minimal economic impact to the operators. Service experience gained on current and past design practices, together with full-scale fatigue testing and teardown inspections of in-service structure, is reviewed to show that design lessons learned are essential ingredients of the aircraft structural improvement process. Several examples are given to show aircraft structural performance improvements in fatigue, durability, damage tolerance, and corrosion. Finally, the current tendency of operators using the airplanes beyond their original design service objective is recognized, and ways to accommodate this are discussed.

INTRODUCTION

The airplane industry has an excellent safety record. This is achieved, for the aircraft structure, through diligent attention to all of the structural aspects – detail design, testing, manufacturing, maintenance, and inspection procedures. All of these structural aspects have been improving over the past few decades. Simultaneously, regulatory requirements that establish the minimum design standards have also been evolving over the past several decades. The prime challenge facing the airline industry now is to integrate successfully the safety requirements and the design standards with the operational activities, for continued safe and economic operation of the airplanes.

This paper presents a broad overview of the Boeing aircraft structural improvements in both design and technology, to ensure that continued airworthiness of airplanes is maintained with minimal economic impact to the operators. The structural improvements are the result of a structural improvement process which is discussed below, along with several examples of structural performance improvements in durability, damage tolerance, and corrosion.

THE BOEING STRUCTURAL IMPROVEMENT PROCESS

The Boeing structural improvement process has three essential elements:

- Test and service experience
- Technology standards developments
- Implementation of design lessons learned.

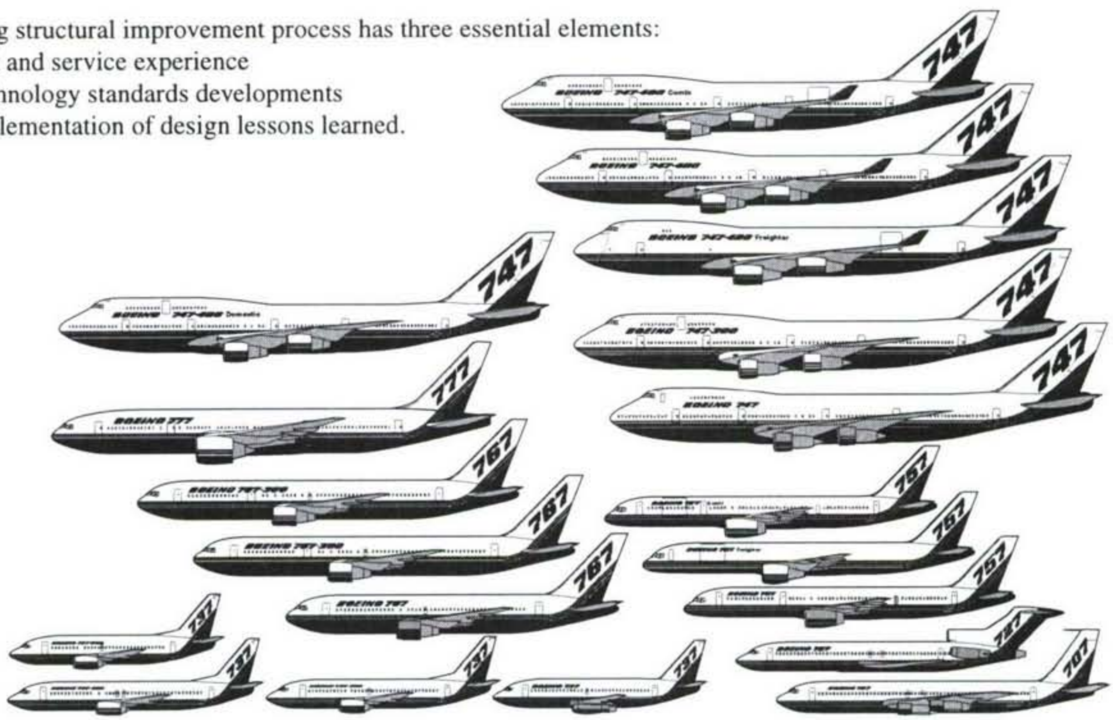

Figure 1. Boeing Family of Airplanes

The structural improvement process is a continuous, living process at Boeing — as improvements are identified, they are implemented in the next possible production line number. This can be illustrated by figure 1, which shows the Boeing family of airplanes. The first generation of Boeing jet transports was designed in the 1950s and 1960s. These are the 707, 727, and the earlier production models of the 737 and 747. The second generation of Boeing jet transports are the 757, 767, and the current production models of the 737 and the 747. The third generation of Boeing jet transports are the 777 and the 737-NG (Next Generation). As design upgrades are developed, they are incorporated into the production of these airplanes as appropriate. Thus, the structural improvement process at Boeing is a continuous, living process.

A brief discussion of the structural improvement process elements is given below:

Test and Service Experience

The first and the foremost element of the structural improvement process is the development of structural performance data from the full-scale fatigue testing and teardown inspections of in-service aircraft structure. Structural performance data provide validation of the design for assurance of safety as well as for economic operation of the airplane.

Full-Scale Fatigue Testing

Full-scale fatigue testing of airplanes is a major part of Boeing structural performance data development. In addition to providing the validation of aircraft design concepts, full-scale fatigue testing is often used to identify any preventive maintenance actions for the fleet, if the fatigue testing is done at the time of certification of a new model of jet transport (which is often the case at Boeing).

Airplane	Minimum design service objective	Fatigue test cycles	Remarks
707	20,000	50,000	Fuselage Hydro-fatigue test
727	60,000	(a) 60,000	Complete airframe
		(b) 123,000	Complete fuselage 47,000 cycles in service plus 76,000 pressure test cycles
737	75,000	(a) 150,000	Fuselage section/pressure and shear
		(b) 129,000	Complete aft fuselage 59,000 cycles in service plus 70,000 pressure test cycles
747	20,000	(a) 20,000	Complete airframe
		(b) 40,000	Complete fuselage 20,000 cycles in service plus 20,000 pressure test cycles
		(c) 60,000	747-400 sections 41and 42 pressure test cycles
757	50,000	100,000	Complete airframe
767	50,000	100,000	Complete airframe
777	40,000		Complete airframe (1st quarter 1995)

Figure 2. Full-Scale Fatigue Test Programs

- 707 wing plus center section 1965
- 707 wing 1968
- 707 wing plus center section and fuselage 1973
- 707 empennage 1978
- 727 forward fuselage 1978
- 737 wing plus center section, forward fuselage, and empennage .. 1987
- 737 aft fuselage 1988
- 747 wing and empennage 1989
- 747 fuselage 1991
- 727 wing and empennage 1994
- 727 fuselage 1995

Figure 3. Teardown Inspection of In-Service Structure

Figure 2 shows the Boeing airplane model, the minimum design service objective (DSO) in flight cycles and the full-scale fatigue testing in flight cycles. It may be seen from figure 2 that full-scale fatigue testing is generally accomplished to twice the minimum DSO, with two exceptions. The first exception is the model 727, which was originally fatigue tested to its DSO of 60,000 flight cycles. However, approximately two years ago, Boeing acquired a 727 airplane with 47,000 accumulated flight cycles and cyclic pressure tested the fuselage to an additional 76,000 cycles. The second exception is the model 747 which was also originally fatigue tested to the DSO of 20,000 flight cycles. As in the case of the 727, Boeing acquired a 747 airplane with 20,000 accumulated flight cycles and cyclic pressure tested the fuselage an additional 20,000 cycles. In addition, the fuselage sections 41 and 42 of the derivative model 747-400 were cyclic pressure tested to 60,000 cycles, representing three DSOs.

Teardown Inspection of In-Service Structure

Teardown inspection of in-service aircraft structure is the other part of the structural performance data development. For this purpose, suitable high-flight-cycle airframes are acquired and disassembled for inspection, to allow a detailed assessment of structural integrity. Figure 3 shows a chronological listing of teardown inspections performed on some key airframe components of various Boeing airplane models.

Full-scale fatigue testing of airplanes, major component fatigue testing, and teardown inspections generally require extensive test setups and test facilities. Figures 4 through 8 show some of the test setups at Boeing to accomplish these tests.

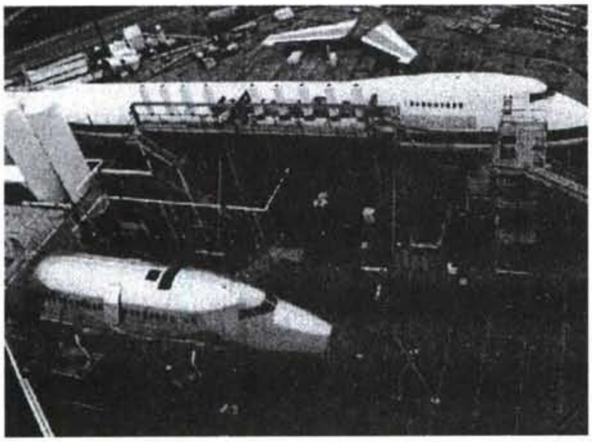

Figure 4. Cyclic Pressure Testing of 747 Fuselage Structures

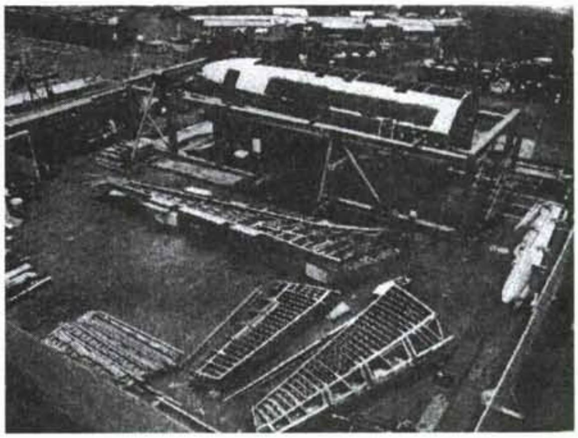

Figure 5. Cyclic Pressure Testing and Teardown Inspection of a 737

Figure 4 shows the cyclic pressure testing of a retired 747 fuselage. This figure also shows, in the foreground, fuselage sections 41 and 42 of a later-design 747 being fatigue tested.

Figure 5 shows the cyclic pressure testing of a retired 737 fuselage. The wings and the fuselage of this airplane were torn down for detailed inspection.

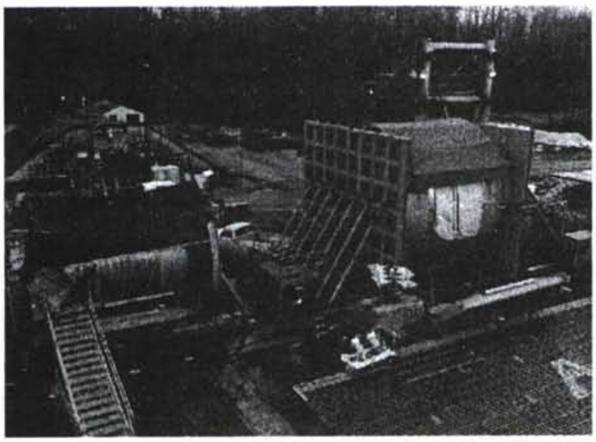

Figure 6. Pressure Barrel Test Setup

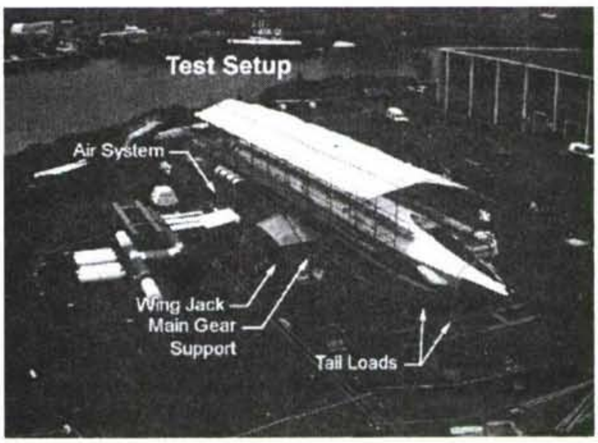

Figure 7. Cyclic Pressure Testing of a 727 Fuselage

Figure 6 shows the test setup for what is called "pressure barrel testing," where large fuselage panels are cyclic pressure tested. There is a pressure barrel test setup for standard body airplanes and another setup for widebody airplanes. Pressure barrel testing is a very convenient way to test design concepts and repair modifications for fuselage structure.

Figure 7 shows the cyclic pressure testing of the fuselage of a retired 727 airplane.

Figure 8 shows a representative fuselage section of a 777 airplane being subjected to fatigue and damage tolerance testing, during the development of the airplane design.

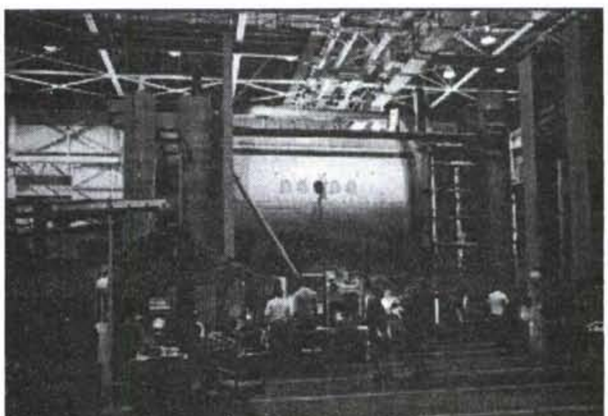

Figure 8. Fatigue and Damage Tolerance Testing of 777 Fuselage Section

Technology Standards Development

The second element of the Boeing structural improvement process is the development of structures technology standards. Figure 9 shows the extensive resources Boeing devoted to the technology standards development, chronologically. From the early 1970s, Boeing devoted extensive efforts to develop methods and allowables for enhanced analysis capability for new and aging aircraft structure. Significant amounts of testing – coupon, component, as well as full-scale fatigue testing and teardown inspections – served as verification and validation of Boeing technology standards development.

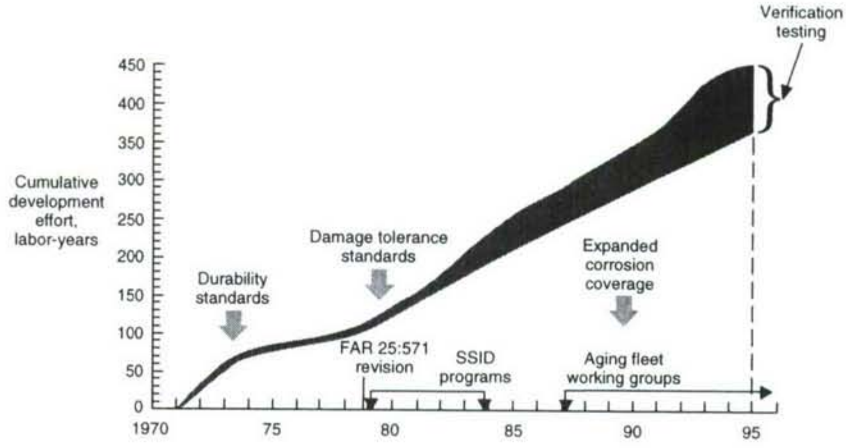

Figure 9. Boeing Technology Standards Development

Durability standards were developed first, followed by damage tolerance standards. These two standards were incorporated into the designs of the second generation of Boeing jet transports, the 757 and the 767 models. The Boeing damage tolerance standards were utilized in the certification of the Boeing models 757 and 767 as damage tolerant per the Federal Airworthiness Regulation 25.571, Amendment 25-45. The Boeing damage tolerance standards were also utilized in the supplemental inspection documents (SID) of aging airplane programs for the Boeing models 707, 727, 737, and the 747.

From the early 1970s, corrosion has been recognized as one of the dominant factors in the inspection/maintenance activities of airline operators. Boeing has devoted extensive resources to the technology standards development in the areas of corrosion prevention and corrosion control. Expanded corrosion coverage, as a result of the corrosion standards development, was incorporated into the production lines of all current production airplanes as well as the aging fleet working groups.

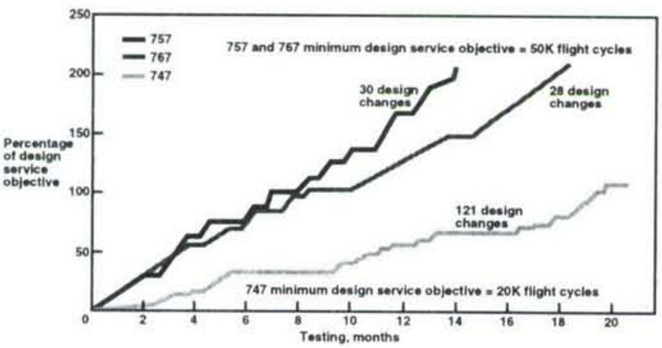

Figure 10. Major Airframe Fatigue Targets

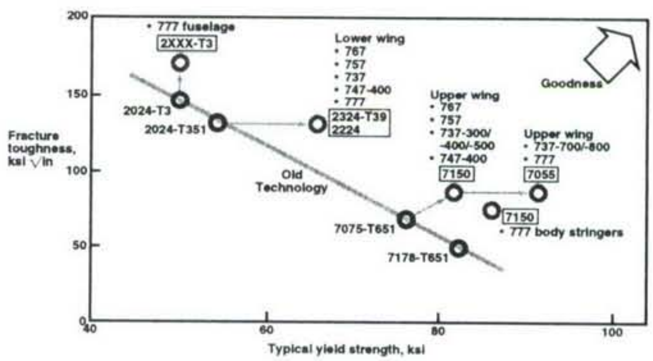

Figure 11. Boeing Structural Aluminum Alloy Improvements

The significance of Boeing durability standards development to the structural improvement process can be illustrated by figure 10, which shows full-scale fatigue test cycles versus testing time for the three Boeing airplane models, 747, 757, and 767. It may be seen from this figure that the Boeing second-generation jet transports, 757 and 767, were tested to twice their respective DSO in flight cycles, in less time than it took to test the Boeing first-generation jet transport, 747, to its one DSO in flight cycles. More significantly, the design changes identified in the 757 and the 767 fatigue testing in two DSO flight cycles are far fewer than the design changes identified for the 747 during its fatigue testing for its one DSO in flight cycles. This improvement is due to the fact that durability technology standards were incorporated into the designs of both the models 757 and 767.

Improvement of aircraft structural materials is a part of Boeing technology standards development. Figure 11 illustrates improvements in several structural aluminum alloys and their applications to the airframe over the past few decades. Conventional 2000 and 7000 series aluminum alloys are represented as the "old technology," where the fracture toughness decreases with increases in the yield strength. Improved aluminum alloys were developed which have higher fracture toughness and/or higher yield strength than their counterparts in the old technology. For example, aluminum alloy 2XXX-T3 was developed as the 777 fuselage skin material. The fracture toughness (K_c) of this alloy is higher than that of the 2024-T3 alloy. Similarly, the upper

wing skin material used on Boeing models 757, 767, 737-300, -400, -500, and 747-400, is the aluminum alloy 7150, which has higher fracture toughness as well as higher yield strength compared with the traditional aluminum alloy 7075-T651. The upper wings of the Boeing third-generation jet transports, 777 and 737-NG, are made of aluminum alloy 7055, which is further improved from the alloy 7150.

In comparison with metallic materials, advanced composite materials offer potential advantages in structural weight, durability, damage tolerance, and corrosion resistance. However, two major challenges must be resolved before these benefits are captured in the commercial aircraft fleet around the world; affordable initial cost, and proven commercial in-service operation. The Boeing technology standards development in advanced composites, is directed to address these challenges. The intent is to develop a progressive approach to composite primary structures that are both performance and life-cycle-cost competitive with today's metal technology. As the first step in this progressive approach, Boeing selected advanced composite materials for the horizontal and vertical stabilizer structures in the design of the 777 airplane.

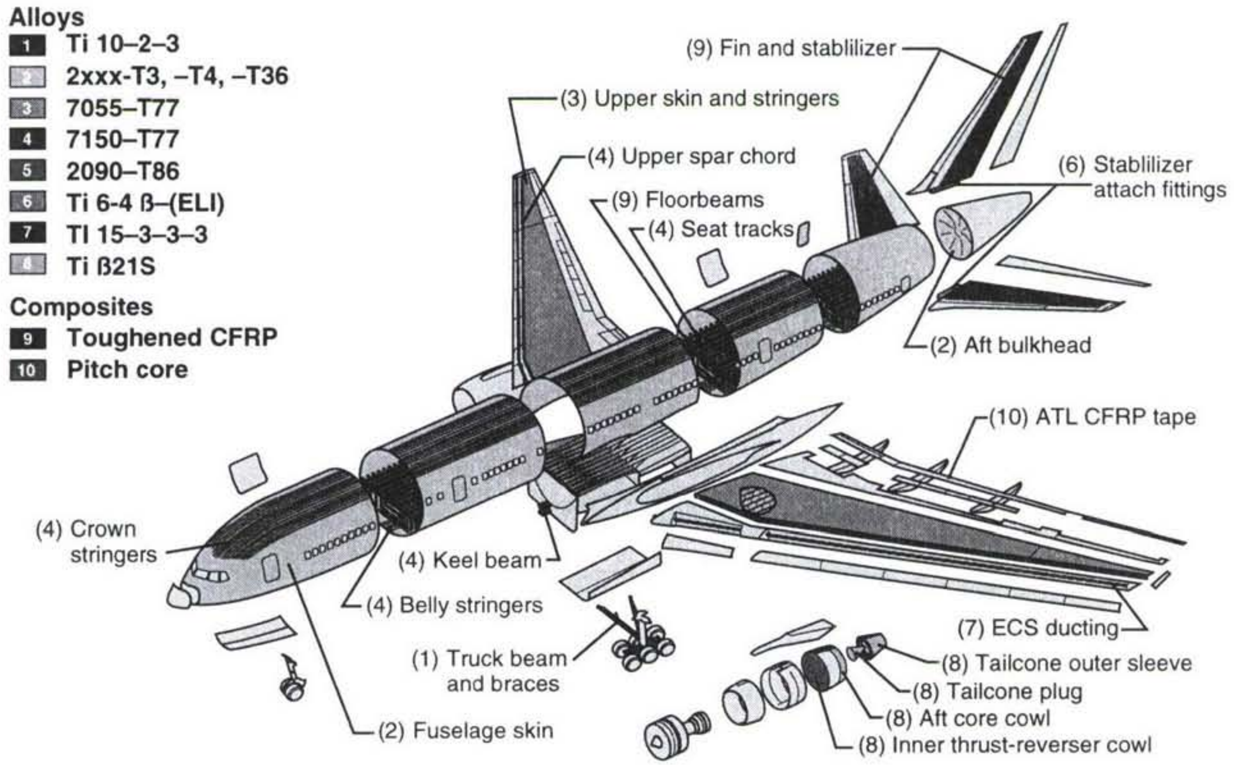

Figure 12. Boeing 777 Advanced Materials Use.

Research and development of aircraft structural materials led to the utilization of advanced materials, both metallic and composites, in the construction of the Boeing model 777 airplane. This airplane has utilized more advanced structural materials than any previously built by Boeing. Principal structural materials of the Boeing model 777 are shown in figure 12.

Implementation of Design Lessons Learned

The third element of Boeing structural improvement process is the implementation of improved designs based on lessons learned from past design practices and the new technology in the production lines at the factory. For example, in the area of corrosion prevention and corrosion control design, a number of design improvements have been identified and incorporated into the production of 747 airplanes. Figure 13 shows a number of key improvements and their incorporation into production, by calendar year as well as production line number. As can be seen from this figure, a later production line number of the airplane has all of the design improvements identified until that time. Design improvements identified for any Boeing model airplane are also incorporated into the production lines of other Boeing model airplanes, if appropriate.

The beneficial effect of corrosion prevention design improvement on the 747 can be illustrated by figure 14. The metric chosen here is "corrosion events reported in the first ten years of service." Comparison of this metric for two structural components for the preimprovement and postimprovement 747 airplanes, shows that the design improvements are very effective for corrosion prevention.

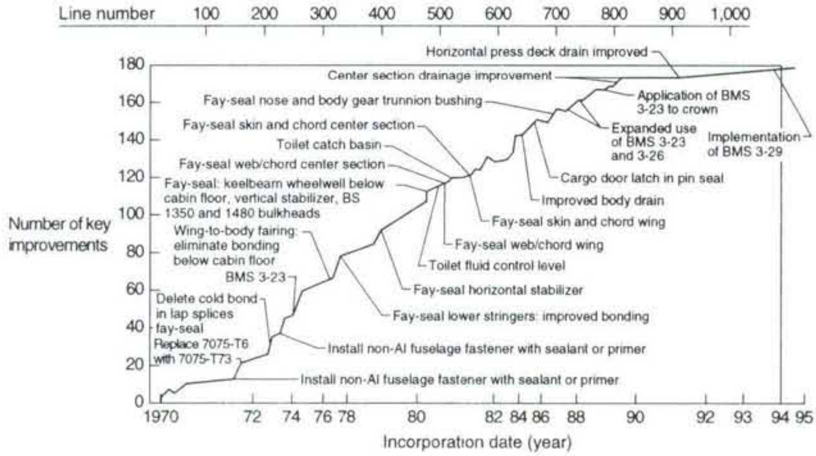

Figure 13. 747 Corrosion Prevention Design Improvements

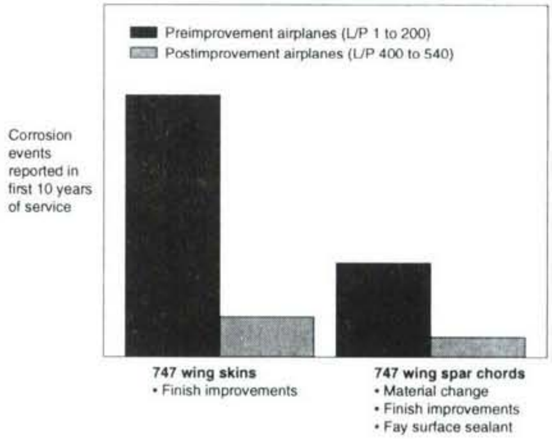

Figure 14. Effects of Corrosion Control Improvements on the 747

Another metric for the effectiveness of the design improvements is "maintenance labor-hours per airplane to address corrosion and fatigue for the first ten years of operation." In figure 15, this metric is compared for two widebody airplanes, the 747 and the 767. This figure illustrates two points:

1. For both the 747 and 767 airplanes, the maintenance labor-hours to address corrosion and fatigue decrease with increase in production line number; later production line numbers for the 747 and the 767 airplanes are improved with respect to corrosion and fatigue.

2. The second-generation 767 airplanes have much better corrosion and fatigue performance, compared with the first-generation 747 airplanes. As discussed before, this is because of the implementation of all the lessons learned from past design practices in the design of new airplanes.

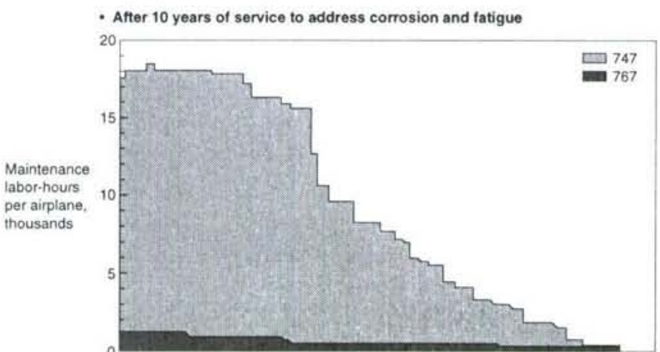

Figure 15. Service Bulletin Labor-Hours (Widebody)

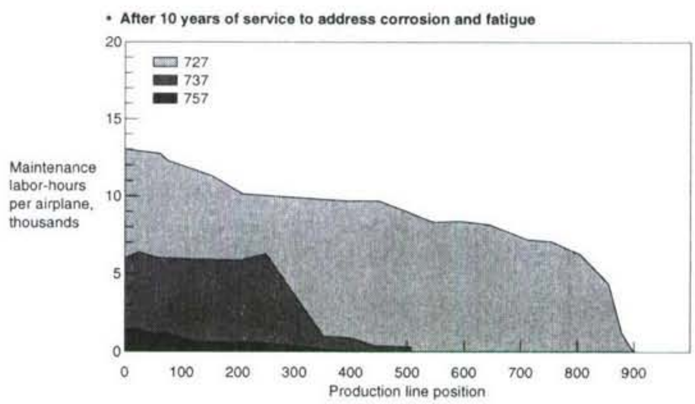

Figure 16. Service Bulletin Labor-Hours (Standard body)

Similar conclusions can be drawn for the standard body airplanes (figure 16). Labor for corrosion and fatigue-related maintenance is much less for the second-generation 757 airplanes, compared with the first-generation 727 and 737 airplanes.

Worldwide airplane fleet support is an important objective for Boeing. The Boeing structural design technology improvements have a vital role in accomplishing this objective. Current airplanes are in service longer than their original DSO. It is expected that this trend will continue for sometime in the future. Structural design technology improvements provide rational means to achieve this increased DSO for the operators by developing, under the auspices of the structures working groups, supplemental inspections, aggressive corrosion prevention and corrosion control programs, and any required structural modifications.
A chronological summary of the Boeing structural design improvements as they support the airplane fleet is shown in figure 17.

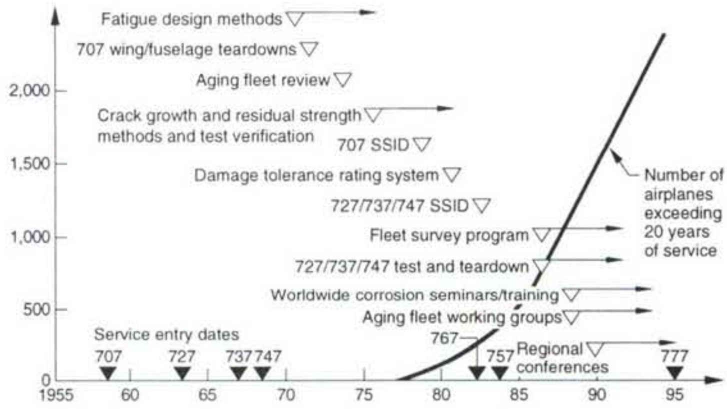

Figure 17. Boeing Fleet Support Actions

SUMMARY

Current production airplanes have significantly improved structural performance; they are more durable, damage tolerant, and corrosion resistant than the previous-generation airplanes. This improvement in structural performance is because of a continuous structural improvement process, which identifies design upgrades based on technology standards and design lessons learned from past design practices, testing, and service experience. These design upgrades are incorporated into production as soon as possible.

This structural improvement process is validated by service experience and provides confidence for increased design service objective of the airplanes with minimal economic impact to the operators for continued airworthiness.

MAINTAINABILITY OF COMPOSITES

Michael J. Morris
British Airways
London, Heathrow

ABSTRACT

The trend towards the use of composite structures in the civil airline field has been sedate but deliberate. The driver has been the necessity to reduce operating costs by reducing the overall airframe weight.

Conventional aluminum structures are what the majority of the airline industry has grown up with. We know - in the main - how they behave and what to look for when subjected to the rigors of routine operations. We know how to tailor our maintenance programs dependent on local environmental conditions, route structure, and our operational demands. We know what to look for following unusual events such as spillage, fire damage, impact etc. We have refined our inspection and maintenance standards and, in recent years, extended a great deal of time and effort into the necessary actions required to maintain the integrity of the conventional metallic structures into and beyond their design life goals.

This paper discusses some of the current problems associated with maintaining composite structures and the impact it is having on airlines.

INTRODUCTION

Composite material usage has increased to typically represent 10-20% of all structural weight in current aircraft design.

For the operator, this now represents a significant percentage of structure requiring a new range of engineering skills, materials, and equipment to maintain. It has also necessitated the adaptation of existing inspection methods and the development of new inspection techniques to ensure the continued integrity of these structures. The importance of these facts has been focused in the last few years by the number of Airworthiness Directives which have been issued on such structures.

In addition to these new maintenance and inspection skills, the operators (and in many cases the OEM) have been attempting to understand and quantify what any given damage means in terms of residual strength and most importantly, what the propagation rate of any acceptable damage will be. Generally we find that allowable damage is extremely conservative, if quoted at all, which leaves the airline engineer to make subjective decisions often under considerable operational pressures. Damage propagation rates are an extremely important factor for the operator if he is to strike the correct balance between the economics of his inspections (method and frequency) and maintaining safety. It is recognized that this is an area of extreme complexity due to the variation in design, build technique, and materials used by the OEM's. Generally speaking, these parameters differ so greatly that there are no definable rules as we generally understand them and as are applied to conventional structures (Fatigue Propagation Rates).

COMPOSITE STRUCTURE (?)

"Janes Aerospace Dictionary" defines composites as "structural materials made up of two or more contrasting components, normally fine fibers or whiskers, in a bonding material."

Such a simplified definition defies the vast array of structures we now class as composites. They vary between a number of different metallic/fiber and carbon cores and skins in as many combinations and variations as can be conceived. In addition, we find a combination of machined and/or fabricated members bonded to a variety of cores using a variety of bonding agents. These types of structures can be designed for use as tertiary (fairing) structure through to primary flying control surface and lift device structure. Solid carbon structures have at least, in the commercial aviation world, been reserved for primary load bearing applications.

For an airline such as British Airways, who operate a large fleet of ten aircraft types from five manufacturers, the variety of composite designs and the resultant complexity in design and in the materials and processes used, create considerable problems for maintenance and repair. In particular Concorde (for which some airframes are approaching their currently approved life goal) is demonstrating some testing problems. The primary flight control surfaces are composite structures which have operated many thousands of flights (~6,000) at supersonic speed (Mach

2+) in conditions of heat and ultrasonic vibration not normally encountered by such structures on conventional aircraft. When the first in-flight damage to a Concorde rudder occurred, some five years ago and with no retrieved failed parts to examine, an assumption was made that some form of impact damage instigated a rapid failure. However, trailing edge disbond was suspected as a result of paint stripper entering the bond line and an nondestructive testing (NDT) ultrasonic inspection was introduced at the trailing edge. Following additional problems, a repeat four flight inspection of the trailing edge and an eight flight inspection of the remaining area was introduced. Realizing that this regime could not continue, all rudders were removed and sent to a specialist center for immersion C-scan inspections which, being a more sensitive technique detected many more areas and potential areas of disbond. This caused considerable disruption to the operation of Concorde as the repair of the structure was complex and time consuming. To enable the operation to continue and because under such conditions so little was known about the aging effects and disbond propagation rates on the structure, that a damage limit of one square inch was set with a repeat monitor inspection of three flights only. It does not take much imagination to realize the resources required to continuously inspect for a square inch defect and less still to appreciate that the probability of missing such a defect would be relatively high. Inevitably the only acceptable long term answer was to build a complete set of new surfaces at considerable cost.

MAINTENANCE

Maintenance is a complex issue - however, for the purposes of this paper, I shall address the two main elements - Inspection and Repair.

INSPECTION

Initially this will be driven by the MRB, followed by the OEM's Planning document which in turn is translated by the operator into a maintenance specification. Historically, these inspections have generally been visual (surveillance level) occasionally supported by a tap test. For secondary structure this method has proved mainly satisfactory and only if economics dictate would a more sophisticated inspection technique be employed. For primary structure the

operator is increasingly having to employ more reliable ways of detecting damage to ensure continued integrity. These methods include X-rays, ultrasonics, thermography, and C-scan techniques. They all need specialized technical engineers to accomplish and inevitably have additional requests: X-rays - no people on or near the aircraft; thermography - access required to aircraft within thirty minutes of landing; C-scan requires the part to be removed from the aircraft.

The inspection effort is directed towards one thing only - disbond - and the main agent provocateur is moisture, followed by manufacturing/processing problems, and corrosion of aluminum honeycomb cored structures. X-rays and thermography will successfully detect moisture; they will however equally successfully detect excess bonding and/or filling agent. Neither however are necessarily able to confirm if any associated disbond has occurred. Experience (usually very costly) can however dictate that a predetermined level of detectable moisture is cause for removal and repair. In the case of a sufficiently high moisture intake and dependent on location, serious (flight control) unbalance has resulted and indeed Airworthiness Directives released to address the situation.

The ultrasonic (single side or through transmission technique) and C-scan inspections will detect disbond but can be affected by skin thickness and skin-to-core bond-line irregularities.

Once detected, and if no limits are directed, the operator is faced with a decision as to whether the amount of moisture uptake of the area (or disbond) is an airworthiness or economic and reliability issue. The airworthiness issue should be a given "black or white." However, the decision making is often clouded with uncertainties as to what the inspection results are actually telling us. In the event that a particular defect is acceptable for further service, a decision has to be made as to the frequency and method of any repeat inspections.

My present perception is that defect (disbond) propagation rates for most composite structures seem to be an intelligent guessing game and not a science. In consequence, operators have suffered both airworthiness incidents through inadequate inspections and at the same time, continued to grossly overmonitor and inspect some structures. Consequently this is an area of considerable concern for the operators.

The problem of moisture ingress is an age old one and has been a burden on the operators ever since the emergence of composite structures on airframes some thirty years ago. As the use has increased so have the problems - few lessons it would appear have been learned to the extent that British Airways now has a mini industry dealing with (repairing) components that have suffered moisture ingress. The cost to the operation of carrying around moisture soaked components is considerable. In a recent exercise British Airways carried out, it was found that on average, the spoiler panels on a particular aircraft had an average 5 lb. of water entrapped in them. If this were typical for all twelve spoilers fitted, the cost for the fleet was £150,000 per annum. Further, we have invested £600,000 in tooling to be able to repair these items. This is for <u>one</u> item on <u>one</u> aircraft type. Consider for a moment, if you will, the many large area composite panels on a modern wide bodied aircraft and you will understand why I have referred to the repairing of such structures has having grown to be a mini industry.

The inspection standards of solid carbon primary structures is also an area of concern. The airline inspector has to be re-educated in what he is expected to look for. The usual signs of conventional structural distress which his experience tells him requires further investigation will not be manifest. He has to understand that a small dent, which on a conventional structure he would sign off as acceptable, will require in-depth investigation, including internal inspection and/or NDT. Conditional inspections such as post-lightening strike, impact, spillage, heat, etc., will be more subtle.

Although examples of such large structures have been flying commercially for some time, they are still a long way down the learning curve and I wonder what the long-term aging effects will be?

REPAIR

Repairs on wing are inevitably temporary mainly due to the difficulty of either adequately drying out the structure (and therefore having to carry out a low temperature repair) or, if off station, having to install a metallic bolt-on type repair, which generally results in the inability to affect an economic permanent repair at base. The cost of effectively destroying a part to temporarily

maintain a schedule is not accounted for by the designer when considering the economics of composite versus conventional structure.

To remain economic, an aircraft has to be committed to a tight flying schedule around which its maintenance schedule must, in turn, be planned. The ability to carryout an effective permanent repair on anything less than a C-check is severely restricted by factors such as the environment, the line mechanics skills, facilities, and the time available. If an unscheduled input has to be made, planning difficulties may arise and not only generate immediate high costs but have a scheduling knock-on effect across the fleet.

Suitable material available can be a serious problem. The lack of standardization between manufacturers has resulted in the unnecessary storage of more than one material type which can do the same job but which may not be an approved alternative. This may result in considerable wasted time incurred whilst establishing what is an acceptable alternative and gaining approval. The manufacturers usually do not recognize each other's test procedures and would not provide an approval without subjecting the material to its own set of tests.

Material supply may also be a problem. It is common for a material to be available from only one source, usually in the wrong continent. This may incur a transportation-time penalty. Furthermore, such materials are difficult to purchase in small quantities as is typically required by an airline and may take a considerable time to locate.

The handling and use of composite materials requires skills which differ from those necessary for work with metals. The quality of repair is more operator dependent than for metallic repairs. Time may be lost locating suitably skilled staff, particularly for 'in-situ' repairs which require additional skills to those required in the workshop. Once suitable manpower has been located, then it must be noted that there may be a knock-on effect because this manpower may have been diverted from other work. This may also introduce overtime costs. For example, a three-day hangar repair could take two mechanics from day shift to work overnight. This could have a five-day effect on workshop activity and possibly result in the rescheduling of other work.

Composite materials possess a number of time-dependent characteristics which can be a problem when a severe deadline has to be met. These characteristics include moisture ingress, adhesive cure time and temperature requirements, a clean environment, and materials availability. It is a known fact that a honeycomb structure can double its weight due to liquid uptake, and it is this liquid that poses a big headache in the workshop and on wing.

In the hanger it is almost impossible to guarantee adequate drying, and a clean environment is not practical. Repairs are therefore of the cold-set type and although often classed as permanent - inevitably fail within a short time due to disbond and further moisture ingress. In the workshop where a permanent (hot-set) repair is expected, many days are spent oven drying components to ensure that the part will not be destroyed by gas expansion during the repair cure cycle. This drying out stage whilst being absolutely critical can add four days or more to the repair lapsed time. It is often therefore, responsible for preventing an adequate turnaround time to meet the aircraft's ETS, thus necessitating purchase of a new part.

It is becoming increasingly more apparent to the operator that the material and extended down-time costs for the repair of composite structures are factors not taken into account at the design stage or in the operational economics of the aircraft.

CONCLUSION

- Currently, the operational cost of composite structure maintenance is significantly compromising the weight benefits which should result from the use of such material.
- The design to prevent moisture ingress must be improved now to reduce the drastically increasing cost of repair and operational economics.
- Composite structures need to be more tolerant of damage, and defect propagation rates need to be better understood.
- Aluminum honeycomb cored structures, due to their extremely poor corrosion record, should be avoided or disused entirely at the design stage.
- The time factor for repairs must be reduced and the development of an effective rapid low-temperature cure structural resin is essential.
- The use of standard materials between OEM's must be urgently promoted.
- It is recognized that the Commercial Aircraft Composite Repair Committee (CACRC), which consists of manufacturers, suppliers, operators and regulatory authorities, are tackling many of these issues. I would urge you all to support their activities more vigorously.

HUMAN FACTORS IN AVIATION MAINTENANCE: CURRENT FAA RESEARCH

William T. Shepherd
FAA-Office of Aviation Medicine
Washington, DC
and
Colin G. Drury
State University of New York at Buffalo
Buffalo, NY

INTRODUCTION

FAA's Office of Aviation Medicine (OAM) has for the past several years conducted an extensive program to study human performance in aircraft maintenance and inspection. The program has engaged primarily in pragmatic applied research in support of air carrier maintenance management as well as those of the FAA Aviation Safety Inspector (ASI) workforce. This paper describes a few of the pertinent research tasks currently being performed. These selected tasks fall within three programmatic areas:

1. Improving Human Inspection Reliability
2. Advanced Technology in Training, Job Aiding, and Documentation
3. Technician Resource Management (TRM)

This paper will focus primarily on the first of these areas.

DISCUSSION

Improving Human Inspection Reliability

The inspection system for airframe and engine components is a generally reliable one, despite the known unreliability of each specific inspection process step. The challenge in designing and running inspection systems has always been to achieve the highest level of system reliability at minimum cost of inspection equipment, inspection time, and aircraft out-of-service time.

In inspection reliability improvement, there have been two broad methods of advance, without much evidence of overlap:

1. **From the Human Factors Engineering side.** Here the basic precept is that a mismatch between task demands and human capabilities leads to system-induced human errors. Explicit, often quantitative, models of the human (e.g., decision theory, signal detection theory, visual search theory) are used to predict the types of errors which can arise. This process then drives inspection system improvement, changing the task, the operator (inspector), machine, or environment as appropriate, e.g., review in Drury, 1992 (Ref. 1).

2. **From the Nondestructive Inspection (NDI) Reliability side**. Here the basic precept is that all defects have a probability of less than 1.0 of being detected by real NDI systems, and that this probability must be predicted or measured for safe system operation. The models used are physical models of the structure, the defect, and the detection system, with a degradation factor due to human presence in the system. These models, and associated empirical studies, lead to probability of detection curves where the abscissa is a critical defect characteristic (typically crack length) and ROC (Receiver Operating Characteristic) curves relating true detection to false alarm, e.g., review in Olin and Meeker 1994 (Ref. 2). The process leads to reliability predictions, as a function, for example, of crack length, which drive the setting of safe inspection intervals, e.g., review in Goransen, 1993 (Ref. 3).

In aircraft inspection reliability, these two traditions are beginning to come together out of necessity, e.g., Lock, 1995 (Ref. 4). Indeed, the FAA programs primarily concerned with each are performing joint projects so that a fuller interchange of ideas should be expected in the future. This section examines these two traditions for points of contact, points where each can learn from the other, and why they must be used together in the area of visual inspection.

The Human Factors Tradition in Inspection

Initial observations of aircraft inspection being carried out, and of the methods used to plan and control this activity, suggested that these inspection tasks were little different in concept from those in industrial inspection, which had been extensively studied by direct experimentation to understand the factors affecting performance, e.g., Drury, 1992 (Ref. 1). The differences arose

mainly from the fact that in industrial tasks the inspected items typically come to the inspector; whereas in the hangar, the inspector goes to the specific area requiring inspection. Because of the similarities, it was possible to structure aircraft inspection tasks using a generic function description. Table 1 shows the seven functions which were used in this program and represents the first of many instances of using human factors knowledge to interpret the world of the hangar in terms which allowed the application of human factors techniques.

This structuring was used to study many inspection jobs, each starting with the assignment of a workcard and ending with all items on the workcard being completed and signed off. A task analysis format was developed from the function list of Table 1 and used to generate a list of the subsystems potentially limiting human performance of each subtask (Ref. 5). Both visual and Nondestructive Inspection (NDI) tasks were studied, covering all areas of the airframe and performed at many airlines in the USA and overseas.

From these task analyses came a series of project proposals directed both at better understanding of the aircraft inspection process and demonstration of applications of human factors knowledge. A number of these projects have now been completed and have begun to influence inspection practices in the airlines.

We have also developed system-level integration tools aimed at applying a range of human factors principles in the hangar (Ref. 6). As the Office of Aviation Medicine's *Human Factors Guide for Aviation Maintenance and Inspection* is becoming available, applications are increasing.

Table 1. Generic Function List for Aircraft Inspection

Function	**Actions**
Initiate	Gets workcard, reads, understands, calibrates equipment
Access	Moves to area to be inspected, carrying needed equipment
Search	Scans area, either visually or using equipment, stopping for indications
Decision	Makes decision on whether or not an indication exceeds standard
Response	Writes Non-Routine Repair (NRR) form, marks indication as defect
Repair	Mechanic performs work specified on NRR
Buy Back	Inspector rechecks work performed and signs off, if it meets standards

The projects completed so far and those currently underway are summarized below:

Function Level Interventions

Initiate: Improved Workcards. Used human factors principles to apply improved information design in workcards. Currently being used by three airlines (Ref. 7). Currently applying principles of simplified English to these same tasks.

Access: Work in Restrictive Spaces. Measured the effects of restricted space in a number of inspection tasks and made access improvements at one airline (Ref. 8).

Search: Improved Inspection Lighting. Developed a method of specifying correct mix of ambient, portable, and personal lighting for inspection tasks (Ref. 9). Now used by one airline. Currently measuring the effectiveness of flashlight lens treatments at the Aging Aircraft Nondestructive Inspection Validation Center (AANC).

Decision: Training for Better Decisions. Developed workstation simulators for visual inspection and NDI (Ref. 10) and used visual simulator to demonstrate how an active training program can increase decision accuracy.

Respond: Portable Computer-Based Workcards. Used the principles of good workcard design to design a hyper-media workcard system on a portable computer. Specifically, this simplified generation of non-routine repair forms (Ref. 11). Principles used at one airline to structure their own future system.

Repair Buy Back: International Differences in Team Structure. Studied organization of inspection and maintenance in USA and UK as joint FAA/CAA project (Ref. 12).

System Level Interventions

System Evaluation: Human Factors Audits. Developed portable computer-based programs for rapid evaluation of human factors mismatches in inspection and maintenance workplaces (Ref. 11/13). Now is use at two airlines.

System Integration: Human Factors Teams. Developed a methodology for applying human factors in hangar-floor level interventions. In use at one airline (Ref. 6).

What is not readily obvious from such a list is the detailed knowledge of how task, operator, machine, and environmental factors affect human performance in inspection. For example, the literature on the inspector's response to adverse environments and validated measures of human workload were used to structure the "Restricted Spaces" study and non-FAA-sponsored research which has followed from it, e.g., Reynolds, Drury, Cerny and Sharit, 1994 (Ref. 14).

Inspection Reliability Measurement

Since the original "Have Cracks Will Travel" study (Ref. 15), carefully chosen sets of test specimens have been inspected by a number of inspectors and the results in terms of relative frequency of detection counted for each test specimen. The system, comprising the NDI equipment and the human inspector, is evaluated by plotting probability of detection against (usually) flaw length to obtain the required PoD curve.

Choice of flaws is based upon their physical properties, and great care is taken to either characterize naturally occurring flaws or grow highly realistic flaws from, for example, EDM notches. Choice of equipment is either prespecified as one particular machine or as one which is acceptable for a particular procedure according to a technical manual. Choice of inspector and environment is made using common sense principles based upon experience of NDI use. Thus, for example, inspector training is carefully controlled; type of inspection facility is varied systematically, or inspection conditions are controlled. There are written codes of practice for setting up and running NDI reliability evaluation, e.g., Rummel, 1982 (Ref. 16).

Analysis consists of mathematical curve fitting to the PoD data, using a range of techniques, e.g., Rummel, Hardy and Cooper, 1989 (Ref. 17). Increasingly sophisticated methods of PoD analysis, e.g., Hovey and Berens, 1987 (Ref. 18), are available now and have been used proactively in large scale studies, e.g., Spencer and Schurmann, 1994 (Ref. 19).

Interactions Between the Two Traditions

While these two methods of inquiry have been presented as separate, they do have points of contact and overlap. In the outcome they have the same goals, i.e., quantifying performance of a human/machine system and predicting the effect of human and system changes on that performance. In their modeling they also have overlap. Both have used Signal Detection Theory (SDT) as a model for human inspection performance; indeed, the work of Swets (Ref. 20/21) is recognized as fundamental in both disciplines. ROC curves appear in both the industrial inspection literature, e.g., Drury and Addison, 1973 (Ref. 22), and in the NDI literature, e.g., Rummel, et al., 1989 (Ref. 17).

However, there is much which the two traditions can profitably learn from each other to provide the more integrated studies and guidelines required by the industry. For example, the log logistic regression models of Hovey and Berens (Ref. 18) should be applied more widely in human factors studies where there is a single flaw parameter driving performance. This could have been used in the study of tactile crack detection for aircraft bearings (Ref. 23) where crack width was the flaw parameter.

Equally well, the NDI reliability studies could benefit from human factors input. For example, the generic function description of Table 1 differentiates between search and decision aspects of inspection. This split is recognized explicitly in some human factors analyses, such as the bearing inspection study by Drury and Sinclair, 1983 (Ref. 24). Here, the analysis was able to differentiate between visual search failure and decision failure, an important outcome as search and decision performance are affected by quite different factors. These authors were able to provide much more specific recommendations as a result of this analysis. A second example of learning from human factors studies is in the area of individual differences in inspection performance. There is considerable evidence that traditional training and years of experience have little effect on the ability to detect flaws, e.g., Kleiner and Drury, 1993 (Ref. 25), but these are often the variables included in quantitative NDI studies where the authors appear surprised to find once again only small differences if any, due to these factors. Again, cognitive styles such as field independence have been shown to be good predictors of inspection performance (Ref.

26), but measure of these styles (e.g., with the Embedded Figures Test) are not typically used as covariates in NDI studies. There is no reason to think that the individual characteristics affecting aircraft NDI performance should be radically different from those affecting electronics testing, use of underwater dye penetrant techniques, or modern air cargo inspection equipment.

A Program Combining Both Traditions

Visual inspection of aircraft structures is the topic of a recent FAA Advisory Circular (Ref. 27) and a topic of great interest to aircraft manufacturers and airlines. If visual inspection performance can be improved, fault tolerant design will require less frequent inspection intervals for the same level of public safety. Recently, the FAA has instituted a program to measure and improve visual inspection: the Visual Inspection Research Program (VIRP). For this program, both traditions are required as visual inspection is used to detect more than just well-defined cracks. Indeed, visual inspection is not even limited to vision, as active tactile (haptic) search supplements vision to detect corrosion and loose and worn parts.

The current VIRP experiments include both a benchmark study (Ref. 28) and parametric experiments to evaluate potential improvements. The benchmark study includes both on-aircraft inspection tasks, using the AANC's B-737 test bed, and visual inspection of well-characterized rivet cracks in the off-aircraft panels. Thus, for the on-aircraft tasks, overall detection probabilities will be measured for a range of defect types to provide data for system reliability calculations; while for the rivet cracks tasks traditional PoD curves and ROC curves will be calculated.

The VIRP studies follow the recent line of combined human factors and NDI studies (Ref. 19/29) in using methods from both traditions. For example, in the rivet cracks task, a differentiation can be made between search and decision failures to give overall, search only, and decision only PoD curves. Similarly, measures of individual differences which are known to correlate with inspection performance, such as the Embedded Figures Test, Peripheral Visual Acuity (Ref. 30) and a Mechanical Comprehension Test (Ref. 31) are being used as covariates to reduce the effects of person-to-person variability on system comparisons.

In response to an applied problem, that of measuring and improving aircraft visual inspection performance, both aircraft NDI reliability and human factors engineering methods have to be utilized. This effort is forcing cross-disciplinary interaction which will ultimately benefit both NDI reliability and human factors in inspection. Visual inspection is an inherently complex activity, examining many different structural elements for many different flaws using many different skills and senses. Because of this complexity, there should be more reason to design future systems as hybrid automation, exploiting the best aspects of both computer vision and human skill rather than seeking purely manual or purely automated solutions. Such hybrid systems have proved superior in other fields, e.g., electronics assemblies (Ref. 32) so that fruitful outcomes can be expected from the conjunction of NDI reliability and human factors in inspection traditions.

Advanced Technology in Training, Job Aiding, and Documentation

Development of the Performance Enhancement System (PENS) is a principal task of the Advanced Technology program area. PENS was primarily developed for use by ASI's but additional applications by airline industry auditors and technicians are being pursued. PENS will be a suite of electronic tools that will supplant current paper-based systems used by ASI's in conducting industry inspections.

ASI's require regular access to a broad range of documentation including regulations, airworthiness directives, service bulletins, and service difficulty reports. They also need to file reports of their inspections to a main frame data base using standard forms. ASI's currently carry clip boards for their reports and cases full of paper documentation to support their inspection information needs. PENS, using hand-held pen-based computers and multimedia software, allows instant screen access to disc or CD-ROM stored information and also facilitates report documentation through on-screen writing capability. Inspection data can later be dumped electronically to the main frame system, eliminating the need for error-prone manual data entry by clerks. Considerable increases in ASI efficiency are expected through PENS use, but just as importantly, data accuracy should be vastly improved.

A field study of PENS in all FAA regions was recently completed to evaluate various hardware/software configurations (Ref. 33). Other electronic ASI job-aiding systems will be studied including digital notebooks and subnotebooks. In all cases it is important to determine optimal system configurations that will efficiently support the unique data and information needs of the FAA while simultaneously recognizing ASI skills and preferences. These human/system interface issues are the primary focus of the Advanced Technology research in the OAM program.

Industry applications to be studied include use of PENS in auditing of suppliers and maintenance activities as well as providing job aiding to technicians as they are working on aircraft. Pen-based computers can be used to provide such information as parts lists, exploded views, repair sequences, and job cards. Beyond this they can be used by technicians to produce reports and forms needed to document their work. Anecdotal information suggests technicians currently spend as much of their time seeking information in paper documentation such as manuals or providing information such as reports as they do in actual hands-on repair work. It is felt that use of electronic job aids can greatly reduce this nonproductive time and allow technicians to spend more of their time in the actual repair of aircraft. A great deal of research is needed in the airline PENS application to identify information needs and preferred means for providing this information. An airline partner is already working with the OAM research program on this task.

Technician Resource Management

CRM or crew resource management has found wide application in the cockpits of commercial airlines so it is not surprising that something like it might be applied in other aviation contexts. CRM philosophy is no more than a synthesis of well-established teachings from such fields as management, sociology, psychology, and physiology. Concepts of crew coordination, teaming, communication, leadership, and situation awareness, all part of cockpit CRM programs, can be equally applied in maintenance. Experience in the U.S. Air Force showed that forming maintenance technicians into well-defined teams resulted in dramatic improvements in maintenance performance over previous practices where technicians worked independently. (Ref. 34). Current FAA research in TRM (for Technician Resource Management) examines

performance effects of technician teaming and training in situation awareness. Team performance, managed properly, can lead to more efficient and effective production than can the work of an equal number of persons working independently. Maintenance teams need to be trained for the task of working as a group including training in group decision making, development of interpersonal skills, and working with other teams.

As a task of the Aviation Medicine research program, Gramopadhye et al. (Ref. 35) designed team training methods and evaluated them at an aircraft overhaul facility. Technician teams and a group of independent nonteamed technicians performed an engine remove and replace operation. The team-trained group performed significantly better than the nontrained group of individual technicians. The team-trained group made fewer errors and completed tasks with greater accuracy. This group was also better at coordinating and gathering information, conveying information in a timely and accurate manner, and error correction. A correlation exists between team behavior and successful team performance. More research is planned in this area to identify other components of technician teaming.

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The Aging Aircraft Nondestructive Inspection Validation Center - A Resource for the FAA and Industry

Patrick L. Walter[1]
Sandia National Laboratories, Albuquerque, NM
Christopher D. Smith
Federal Aviation Administration Technical Center, Atlantic City, NJ

The Aging Aircraft Nondestructive Inspection Validation Center (commonly designated AANC or The Validation Center) was founded by the Federal Aviation Administration (FAA) in response to the Aviation Safety Research Act of 1988 which mandates that the FAA carry out research and develop technologies to help the aviation industry to (1) better predict the effects of design, maintenance, testing, wear and fatigue in the life of an aircraft; (2) develop methods for improving aircraft maintenance technology and practices including nondestructive inspection; and (3) expand general long range research activities applicable to aviation systems. The AANC validates nondestructive inspection (NDI) technology, provides a quick response capability, assesses the reliability of NDI applications, and performs other projects to support the FAA and aviation industry. Sandia National Laboratories was funded by the FAA in August 1991 to establish the Validation Center at Albuquerque International Airport.

The Validation Center (Figure 1) contains 16,875 square feet of aircraft storage space, 7,762 square feet of office space and 2,230 square feet of conference and laboratory space. Pad space adjacent to the Center comprises another 99,988 square feet. A 27-year-old Boeing 737 aircraft (Figure 2) was acquired as a test bed in November 1992, and the Center began operating in February 1993. McDonnell Douglas DC-9 fuselage sections (Figure 3) were acquired in June 1993. The US Coast Guard donated a Falcon HU25A aircraft (Figure 4) to the Center in June 1994. A commuter aircraft will be the next significant addition to be included among the Center's test specimens. Other aircraft parts and pieces with various defects are included in and are still being acquired for integration into the AANC resource base. The simulation of a working aircraft inspection and maintenance environment in the Center is one purpose of the ongoing activity.

[1] Currently located at Texas Christian University, Fort Worth, Texas

AANC's original mandate was to validate inspection technologies for aging aircraft applications. That validation process involves the assessment of the reliability of inspection systems (including human factors) and estimation of the cost effectiveness of those technologies. Since its inception, the scope of AANC activities has broadened to include activities in structural integrity analysis, repair assessment, and composite structure assessment.

AANC Fills a Critical Void

The FAA's National Aging Aircraft Research Program is concerned that the increasing age of aircraft and the corresponding increase in inspections and inspection frequency could result in the reduced reliability of safety related inspections. Robust technologies having less susceptibility to human and environmental factors are essential to offset the increasing inspection burden. A less obvious but no less important benefit of improved inspection systems is that the development of reliable, cost effective crack, corrosion, and disbond detection systems can reduce possible collateral damage associated with disassembly, reassembly, and modification of airplane structures.

But development alone is not enough. In today's harshly competitive environment, many aircraft operators feel compelled to maintain older inspection systems rather than invest in new systems and training. Without intervention the potential exists for technologies to remain on the shelf, because operators cannot afford the time and resources to pursue validation and reliability assessment necessary to assure themselves, aircraft manufacturers, and regulatory authorities of the applicability of those technologies. This is the need AANC was directed to address.

Validation of inspection technologies, methods, and systems - developed by both government, academic, and commercial organizations - are performed by AANC. If the validation process indicates that a particular system is both capable and reliable, the FAA can allow its utilization as an alternate means of compliance for certain FAA Airworthiness Directives. These Airworthiness Directives often require the disassembly and inspection or modification of the structure. Because the validation process also examines cost benefit issues of new technologies,

aircraft operators can manage their inspection programs with more capable and reliable inspection technologies.

The Validation Process

The validation process is defined as an independent quantitative and systematic assessment of both the reliability and implementation costs of an NDI process. An NDI process is the NDI system and procedures used for inspection, inclusive of the NDI equipment operator, inspection environment, and the object being inspected.

As part of the FAA's National Aging Aircraft Research Program, research and development was funded at a number of institutions. The largest of these was the Center for Aviation Systems Reliability (CASR) comprised of Iowa State University, Northwestern University, Wayne State University, and Tuskegee University. The Validation Center is also available to manufacturers and vendors of commercially available inspection equipment. The validation process addresses evolving NDI processes with varying degrees of maturity. To accommodate this, the validation process is divided into four phases.

In the first or conceptual phase, aircraft inspection requirements are identified along with NDI techniques offering the potential for satisfying these requirements. Theory and modeling occur in the laboratory. Specific items that may be critical to field implementation are considered.

The second, or preliminary design phase involves laboratory testing on representative test specimens. Equipment procedures are developed. Constraints imposed by the inspection facility are considered as are human performance issues.

Phase three is the final design phase. Field experience is acquired by the NDI developers and blind experiments are assessed in which equipment operators have no prior knowledge of specimen flaws. Statistical performance data are gathered. Procedures and inspector requirements are updated.

The final validation phase is field implementation using fully developed test procedures, trained field inspectors, and realistic work environments. Beta site testing often occurs at airline facilities.

Independent of whether the NDI process emerges from the government funded or private sector, the AANC usually becomes involved with activities near the end of phase 2 of the validation process.

AANC's Goals

Specific objectives of AANC include:

- Provide necessary environment (hangar, aircraft structures, equipment, and personnel) to analyze, validate, and demonstrate currently existing, new, and emerging technologies and methods for the nondestructive inspection of aircraft structures, components, and engines.
- Provide FAA with tools to perform comprehensive, independent, and quantitative evaluations of current and new maintenance and inspection techniques.
- Determine the reliability of inspection tasks by quantitatively determining the probability of detection and false call rates.
- Determine the most significant system, human, and environmental factors affecting the reliability of various inspection tasks.
- Recommend technical and procedural improvements for inspection systems.
- Assist the FAA in the development of regulatory and advisory material.

AANC Program Accomplishments

Recent accomplishments of this initiative include:

- publication of a report on aircraft turbine engine reliability and inspection investigations,
- completion of a reliability assessment of eddy-current inspections in airline maintenance facilities,

- experimental strain assessment of an airframe structure to support FAA structural model development,
- publication of an Emerging Nondestructive Inspection Methods for Aging Aircraft report,
- assessment of manual, semiautomated, and automated scanners for aircraft NDI application (reported on in a following article),
- validation of a Magneto Optic Eddy-Current Imager (reported on in a following article),
- establishment of the FAA Sample Defect Library (discussion contained in a following article),
- baseline assessment of the Boeing 737 airframe to determine flaws (discussion contained in a following article),
- quick response support to various FAA aircraft certification offices,
- hosting of both an International Workshop on Inspection and Evaluation of Aging Aircraft and the Air Transport Association's (ATA) Nondestructive Testing (NDT) Forum, and
- performance of over 60 validation exercises on emerging technologies.

Some other activities currently in progress (with industry or outside participants) include a visual inspection reliability experiment with assessment of visual aids (ATA Inspection Network), DC-9 wing box inspection alternate means of compliance (Northwest Airlines, McDonnell Douglas, Northwestern University), halon bottle inspection (American Airlines), multilayer airframe crack detection reliability experiment (Boeing), boron-epoxy structural reinforcement (Delta, Lockheed, Textron Specialty Materials, Warner Robins Air Force Base), repair inspection initiative (various airframers and suppliers), and small-crack detection reliability experiment (Boeing, Technical Oversight Group on Aging Aircraft).

Probability of Detection Studies Remain Cornerstone of AANC

One of AANC's first and most comprehensive projects was an experiment designed to quantitatively determine the probability of crack detection (PoD) associated with eddy current inspection of riveted skin splices. While many studies have focused on this and similar tasks as

performed in a laboratory environment, this is one of the few studies to quantify the PoD under field conditions. The test samples used were similar to actual aircraft lap splices. The experiment was taken to nine facilities, and five inspections were performed at each facility. The experiment presentation was configured to simulate aircraft fuselage. The inspections took place in the environment in which actual aircraft are inspected, were accomplished using the same equipment that would be used in actual aircraft inspections, and were performed by the same people who do actual aircraft inspections.

The eddy current experiment was a tremendous success in the sense that the results were significant both statistically and technically. The experiment encountered few unexpected problems producing quality data showing the general adequacy of field inspections. An unexpected but very welcome benefit of this study was the exposure of AANC to airline operators, maintenance facilities, and airframers and the cooperative relationship they formed. The nine facilities participated voluntarily and enthusiastically, and Boeing provided very substantial technical support and review. AANC's respect for the sensitivity of the data and excellent execution of the trials and subsequent data analysis, gained for them the respect and goodwill of the industry which has proven vital to the success of many AANC projects.

The next probability of detection study is to assess the reliability of visual inspection. A series of increasingly more specific experiments will assess the effectiveness of directed and non-directed visual inspections. The first experiment utilizes the Boeing 737 and full-scale aircraft components housed at the FAA's Aging Aircraft NDI Validation Center (AANC) to assess the reliability of critical and representative visual inspection tasks. Subsequent experiments will quantify those factors determined in the first experiment to be the critical parameters affecting the reliability of the inspection tasks. The final set of experiments will be designed to examine the benefits of using enhanced visual aids.

In designing the first of these visual experiments, the identification of characteristic and representative visual inspections and the establishment of a test bed proved to be particularly difficult obstacles to overcome. Relying on the goodwill developed during the earlier Eddy-Current Inspection Reliability Experiment (ECIRE) , airline maintenance organizations were

asked to contribute their expertise to the development of the experiments and to supply subjects for the trials. The use of artificially induced flaws was soon ruled out, favoring instead the utilization of the B-737 baseline characterization to identify an appropriate flaw population. Fortunately the results of that baseline and the selection of inspection job cards by the inspection steering committee supported appropriate experimental design.

AANC also performs less extensive formal and informal reliability studies. The goal of these studies is to use the information accumulated to date from 60 different NDI experiments at the AANC to perform data comparisons. These comparisons allow sponsors and researchers to identify promising technologies and to direct those technologies to appropriate inspection applications.

AANC's Quick Response Capability Provides Quick and Direct Support

Since its inception, the FAA's Aging Aircraft Research Program has supported Flight Standards and aircraft certification organizations with medium to long term research. But only with the establishment of the Validation Center has the Program been able to support these organizations in areas requiring short term evaluations of inspection processes.

In October of last year Dr. Alfred Broz, FAA National Resource Specialist for Nondestructive Evaluation (NDE), requested support from the AANC to assist two different aircraft certification offices (ACOs) in solving specific inspection problems. The first request required the AANC to inspect a Hartzell propeller hub assembly for cracks near grease fittings. A report documenting the nondestructive technologies performed on the hub assembly and the results of those inspections were written and submitted to the Technical Center and Dr. Broz within six weeks of the initial request.

In another instance prompted by an accident resulting from in-flight wing separation, the FAA requested AANC to examine and analyze material thinning in the forward wing spar of Piper PA-25 model aircraft. The report, which included examinations of both radiographic and

ultrasonic procedures and a proposed generic ultrasonic procedure to augment the current visual and dye penetrant procedures, was written and submitted to the FAA within four months of the request. The test setup, instrument calibration, and the inspection procedure described in the report may now serve as the basis for a forthcoming Airworthiness Directive. This directive is planned for issuance by the Atlanta Aircraft Certification Office.

Conclusions

The National Aging Aircraft Research Program has established the FAA Aging Aircraft Nondestructive Inspection Validation Center at Sandia National Laboratories in Albuquerque, NM. This center is accessible to airline operators, manufacturers, equipment vendors, and other interested organizations wishing to test or observe the testing of current, enhanced, or emerging maintenance and inspection techniques, equipment, and systems.

Acknowledgments

Other contributors to this work under contract to Sandia National Laboratories include Science Applications International Corporation, AEA Technology, and New Mexico State University.

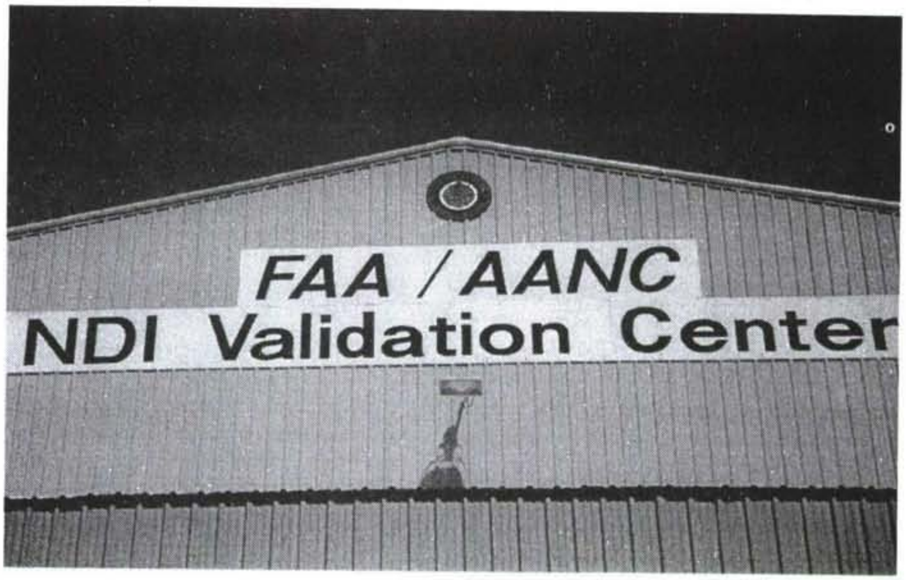

Figure 1. - AANC Validation Center

Figure 2. - B-737 Testbed (46,358 cycles, 38,342 hours)

Figure 3. - DC-9 Fuselage Test Specimen (64,360 cycles, 56,520 hours)

Figure 4. - HU25A Test Specimen Donated to FAA Program by USCG.

NONDESTRUCTIVE TESTING TECHNOLOGY INTEGRATION FOR COMMERCIAL AIRCRAFT OPERATORS

Jeff Register
Northwest Airlines, Inspection Department
5101 Northwest Drive, M/S C8840, St. Paul, MN 55111

ABSTRACT

A number of NDT technology transfer programs now exist within the aviation industry. The Aging Aircraft Research Program was initiated to enhance airline inspection capability. This paper addresses NDT technology integration for commercial aircraft operators and critical issues, such as research subject identification and project management.

INTRODUCTION

To ensure continued airworthiness of aircraft operating beyond original design service life, carriers like Northwest Airlines (NWA) are looking to supplement existing inspection programs with advanced nondestructive testing (NDT) methods. These advanced methods represent potential increases in inspection reliability and cost savings.

Historically, airline carriers have used the five basic NDT methods to supplement visual techniques and minimize structure teardown. Today we see a reversal in the use of NDT. It is now used as a primary method of condition assessment. This can be best illustrated by the supplemental inspection program (SID). The SID program was designed specifically to supplement existing inspection programs to ensure the continued safety of older aircraft as their service extends beyond certification life (1). The SID program allows operators the continue use of aircraft to avoid the high purchase price of new aircraft. It should also be noted that new aircraft hold potential cost savings through NDT applications. Visual inspection requirements in new aircraft may also be supplemented with NDT inspection methods to establish cost savings.

The following section will discuss NDT technology integration to commercial operators, specific deliverables, and issues from a customer's viewpoint.

BACKGROUND

Traditionally, operators have had minimal exposure to NDT technology transfer and research initiatives. Most of this was filtered through the aircraft manufacturer's NDT programs via military initiatives. In 1988 Congress approved the National Aging Aircraft Research Program. This program made available research moneys to enhance current inspection methods and procedures used by aircraft operators. At this point, the airline operators became the technology customer.

The Aging Aircraft Program established two clearing houses for NDT research work: The Federal Aviation Administrations (FAA) Center for Aviation Systems Reliability (CASR) at Iowa State University and the FAA Aging Aircraft NDI Validation Center (AANC) at Sandia National Laboratories. These two centers offer a vast amount of research sources.

INSPECTION PROCEDURES

Advanced NDT methods incorporated into an operator's inspection program must first be documented and included in the operator's procedural format. Generally, these procedures come in two forms: Service Bulletins and Airworthiness Directives. Service Bulletins are recommended procedures and Airworthiness Directives are required compliance procedures. NDT inspection procedures generated by the operator or other entities must have manufacturer and FAA approval if they are to replace existing Airworthiness Directives. Operators who choose to perform inspections, in addition to those required by the manufacturer, do not require manufacturer or FAA approval.

CHOOSING THE RESEARCH SUBJECT

Choosing the subject is the most crucial and often the most misunderstood area of the research initiative. It is necessary to identify the operator's requirements and capitalize on their needs. The problem is, the operator may not be able to identify key research areas. This does not mean the operator doesn't know the aircraft and its inherent problems. It means that today's problem

may be resolved before the research initiative gets under way. The candidate research subject must be fully researched and analyzed before accepting it.

Northwest Airlines uses three general categories to identify key research initiatives: safety improvement, aircraft downtime, and man-hour reductions.

In addition to the above categories, the following questions should be reviewed to identify key subjects:

- What procedures currently exist to resolve the problem (i.e., part replacement)?
- Is there an existing NDT inspection method? If so, will the proposed alternate method reduce man-hours or aircraft downtime? Will the alternate method increase the inspection reliability?
- Will the new method provide flaw quantification?
- Is there a feasible way to field test instrumentation? (i.e., Reference Standards, on-aircraft inspection)
- Will the new method developmental timeframe meet the customer's needs?

ADVANCED TECHNOLOGY - EQUIPMENT JUSTIFICATION

Candidate research projects usually provide deliverables in the form of NDT equipment. If the operator is to take full advantage of the research initiative, it must be able to justify and purchase equipment. Current budget constraints don't make this process an easy one. It is, therefore, imperative that these concerns be reviewed in the initial project research stages.

In addition to safety or inspection reliability enhancements, operators justify equipment on man-hour and aircraft downtime reduction. Specific labor costs vary with each operator. The operator should assist in calculating man-hour cost savings and provide this data to the research team when reviewing the candidate research initiative.

Aircraft downtime cost savings are the savings realized in lost revenue, when the aircraft is out of service for maintenance purposes. Alternate methods of inspection which reduce aircraft downtime can utilize this data when justifying equipment, especially if the inspection incurs an

off-schedule visit. Off-schedule visits are maintenance visits which don't fit current downtime schedules. Reducing aircraft downtime can save an operator tens of thousands of dollars a day in aircraft rerouting, crew scheduling, etc. These calculations should also be performed by the operator prior to research initiative commencement.

Another method of reducing aircraft downtime is to increase the flaw detection capability of the alternate inspection system. This can be accomplished by: finding smaller flaws and/or increasing inspection reliability. If a smaller flaw can be detected, the manufacturer may approve an increase in inspection intervals. In this case, an inspection that had an original interval of 500 flight hours may be extended to 1,000 flight hours. Inspection intervals may also be extended, if reliability or probability of detection (PoD) is increased. This is done by utilizing the advanced NDT inspection method to reduce inspection opportunities.

RESEARCH PROJECT MANAGEMENT

Aging Aircraft Research core groups are usually made up of the following personnel: FAA, academia, researchers, NDT vendors, airline operators, and aircraft manufacturers. Program success, in many instances, is determined on how this group functions and interacts. A project manager should be chosen to establish group parameters, functions, and goals. The project manager should be cognizant of the customer's requirements, in addition to the teams functional needs. All aspects of the research program should be meticulously recorded. The project manager should also address outside influences and barriers which arise. Meeting project deadlines is an essential key to project success. The aviation industry's fast pace leaves little buffer for project delays. Operators may miss capital budget allocations which are set at specific timeframes.

The project manager should conduct a postproject review for successes and lessons learned. These factors should be passed along for future groups to share.

WHO IS THE FINAL CUSTOMER?

Research projects which develop into new inspection methods and technology will serve the initial customer if properly conducted. In addition to the initial customer, projects may have influences on other entities, such as military aviation. Aircraft serving commercial roles such as the DC-9, also have military counterparts like the C-9 transport and the DC-10, which also serves as a KC-10 tanker for the Air Force.

Aircraft manufacturers and operators may identify other applications for new advanced NDT methods on similar aircraft structure. Also, other industries may prosper from the technology advancement and are usually kept in the communication loop through research groups and the vendors associated with them.

RESEARCH CANDIDATES

The list below describes some of the existing problems in the industry today. Operators should be contacted to fully understand these and other candidate research initiatives.

- Second layer corrosion detection.
- Second layer fatigue crack detection.
- Improved eddy-current operational thicknesses.
- Flaw detection under fastener heads (ferrous and nonferrous fasteners).
- Single side thickness measurement on nonuniform or complex thicknesses.
- Human factors studies of procedure format and content.
- Miniaturizing ultrasonic and eddy-current probes.
- Noncontact scanner systems.
- Simplified composite inspection systems.

CONCLUSION

The goal of the Aging Aircraft Program and other technology transfer programs within the aviation industry is to 1) provide the end-user with advanced inspection techniques and methodologies and 2) strengthening the industry's ability to perform core research to support such initiatives.

Today's financial environment forces us to best utilize these resources to make these programs successful. This is an attainable goal through cooperative efforts from the government, academia, research facilities, airline operators, NDT vendors, and the aircraft manufacturers.

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An Integrated Methodology for Assessing Widespread Fatigue Damage in Aircraft Structures

Catherine A. Bigelow
and
Paul W. Tan
AAR-430
FAA Technical Center
Atlantic City International Airport, New Jersey 08405

ABSTRACT

The Airworthiness Assurance Working Group, working in cooperation with FAA and other airworthiness authorities, has made significant contributions to improving the airworthiness of the aging fleet of transport airplanes since 1988. However, some concerns still remain. Methodologies need to be developed to predict the occurrence of widespread fatigue damage (WFD) and the combined effects of WFD and discrete source damage. The basic structure of transport aircraft in service today was designed to sustain large, obviously detectable damage through redundancy (fail-safe) and crack arrest features. WFD and its effect on the residual strength were not considered but must now be evaluated, particularly with aircraft being flown beyond their original design service life. A critical element in the FAA R&D program is the development of methods and tools to insure that the residual strength of an aircraft structure is not degraded below its damage tolerance requirements due to the occurrence of WFD.

A practical life and risk assessment methodology, consistent with transport aircraft design and maintenance practices, will be developed. The deliverables of this research will be predictive models, validated by test data, which will be useful in determining the occurrence of WFD and its effect on residual strength. The test data and predictive models will be used to provide guidelines to insure that WFD does not occur during the operational life of the aircraft.

INTRODUCTION

Aging aircraft research activities being conducted worldwide are aimed at developing and implementing advanced fatigue and fracture mechanics concepts into the damage tolerance analysis methodology for the aging, current, and next generation fleets. These activities include the development and implementation of a damage tolerance analysis methodology for widespread fatigue damage (WFD).

As a result of accidents at the end of the last decade, it became apparent that new tools, processes, and approaches would be necessary to determine the effects of aging on the United States (US) commercial aircraft fleet. At that time, almost a third of the aircraft fleet was over 20 years old, and economic considerations were driving the industry toward the retention of older aircraft. Accordingly, Congress passed the Aviation Safety Research Act of 1988 (Public Law 100-591). This Act increased the scope of the Federal Aviation Administration (FAA) mission to include research on methods for improving maintenance technology and detecting the onset of cracking, delamination, and corrosion of aircraft structures.

Table 1 - Age Distribution of Aircraft in US Fleet, December 1994

MODEL	TOTAL	>20 YRS	% > 20 YRS	Bewteen 15 & 20 YRS	% Between 15 and 20 YRS	>15 YRS	% > 15 YRS
Wide Body	925	297	32	133	14	430	46
Standard Body	4477	1496	33	545	12	2041	46
TOTAL	5402	1793	33	678	13	2471	46

Source: World Jet Inventory, Year-End 1994

In response to this mandate, the FAA developed the National Aging Aircraft Research Program (NAARP) to conduct the necessary research. The basic questions to be addressed are (1) how long can aircraft structural life be extended; (2) are the current techniques, methodologies, and analyses used in design, manufacture, maintenance, and inspection adequate; and (3) what are the best methods for dealing with safety-critical information? Research activities are focused on structural integrity, loads analysis, maintenance and inspection technology, and improvements to

training and human performance. The NAARP is intended to (1) meet FAA mission objectives, (2) assess research quality, (3) validate research effectiveness, (4) predict success in an operational environment, and (5) develop methods for deploying research benefits to the user community.

The analysis and prediction of structural integrity address those issues related to operational loads, fatigue, design, testing, structural modifications, repair design, and supplemental structural inspections. Appropriate predictive models and software systems are being developed to deal with aging aircraft problems. Fatigue and fracture models are being developed to assess material characteristics including environmental effects. Analyses resulting from this research are directed toward providing performance parameters for nondestructive inspections (NDI) or developing maintenance procedures or to determine that further substantiation of continued airworthiness is required. Maintenance and inspection activities focus on the assessment of processes and the development and deployment of technology for enhanced maintenance reliability. Research activities are also aimed at inspection reliability assessment and the development of cost-effective equipment and procedures for improving the inspection process. This paper focuses on the structural integrity research within the NAARP.

STRUCTURAL INTEGRITY RESEARCH

The Federal Aviation Administration (FAA) has an ongoing program to take proactive measures to insure that the continued structural airworthiness of airplanes that are operated beyond their manufacturers' projected operational lives are not compromised due to structural degradation caused by aging. The program is based on the premise that given proper design and maintenance, and taking operational discrepancies into account by making appropriate adjustments to the processes associated with aircraft certification and compliance with flight standards, an airplane can be safely operated for an indefinite period. However, improved understanding obtained through research and development of technical issues related to operational loads definition, fatigue, design, testing, structural modifications, repair designs, and supplemental structural inspections is needed. Correspondingly, appropriate predictive models and software systems need to be developed.

In addition to enhancing their in-house research capabilities, the FAA is also forging links with the University research community. To help establish such links, Congress has authorized the FAA to form research centers of excellence (COE). A Center of Excellence in Computational Modeling of Aircraft Structures has been colocated at Rutgers University and Georgia Institute of Technology. This Center is conducting a comprehensive program of research in the focused area of computational modeling relevant to aging aircraft.

The major purpose of the ongoing research in structural integrity is to assess and evaluate the effects of WFD on the residual strength of the structure and its impact on the damage tolerance design practices. Emphasis is placed in establishing a methodology to identify the onset of WFD. The primary goal of this research is to insure that the residual strength of an aging aircraft structure will not be degraded below the design limit levels due to WFD. The effects of WFD on residual strength were not considered during the original certification of most aircraft structures. As a result, methods capable of determining the time at which the onset of WFD degrades the residual strength of a structure below the original certification levels will be developed so that corrective action can be taken to meet certification. One product of this research will be the development of an integrated WFD risk assessment methodology. The methodology will be developed in a modular approach and will include both deterministic and probabilistic analyses. The methodology will be used to identify critical random parameters, such as effects of corrosion, aircraft loads, and MSD and MED patterns. This will enable the FAA to focus its increasingly limited resources on the most critical areas in addressing the effects of WFD. The methodology will also be used by the operators and manufacturers to quantitatively evaluate the continued airworthiness of aircraft structures.

The end products of this research are predictive models and test data which will be useful in determining the point in the life of an airframe at which the residual strength becomes degraded below the original certification levels due to the formation of WFD. The deliverables include technical reports containing descriptions of predictive methodologies, test results, predictive methodology and test correlation, and computer software which implement the predictive methodologies. The resulting technical data will also be used by the Structural Audit Evaluation

Task Group (SATEG) to formulate Special Federal Airworthiness Regulations (SFAR) and Advisory Circulars (AC) which will provide guidelines to establish the onset of WFD in the aging fleet.

Integrated WFD Risk Assessment Methodology

An integrated widespread fatigue damage (WFD) risk assessment methodology will be developed with a modular approach and include both deterministic and probabilistic analysis methods. This methodology will serve two functions. It will be used to identify the critical random parameters in the WFD process, e.g., corrosion, loads (flight loads, landing loads, pressurization loads), and MSD and MED patterns. The identification of the critical parameters will enable the agency to focus its increasingly limited resources on research addressing those areas. The methodology will also enable the quantitative evaluation of the continued airworthiness of aircraft structures. This will provide the operators and the manufacturers with the methodology needed to address the continued operation of the commercial fleet.

Deterministic Analyses

The FAA is funding the development of two deterministic analyses: the discrete source dislocation method and the finite element alternating method.

Discrete Source Dislocation Method - The Discrete Source Dislocation Method (DSD) is under development at Rutgers University through the FAA Center of Excellence in Computational Mechanics for Aircraft Structures. The method uses the distributed dislocation method [1,2] to compute stress-intensity factors. The method combines a very accurate stress-intensity factor analysis with the two-dimensional boundary element method [3,4] and includes the ability to model nonlinear material behavior. The numerical methods are based on micromechanics and complex variables and has been developed as three modules: the Plastic Source Method (PSM), the Crack Source Method (CSM), and the Boundary Element Method (BEM). These methods are based on the systematic use of dislocations and point forces in the form of Green's functions.

The PSM [5] represents plastic deformation in terms of Green's functions; the method is essentially based on the continuous planar distribution of dislocations. The CSM [1-3] simulates a crack by the continuous distribution of dislocation dipoles along a line. The method can model multiple cracks and curving cracks. The BEM [4] includes the effects of stiffeners, fasteners, and other finite boundary effects. The DSD method will be available as a stand-alone code, integrating the three modules, and will operate on personal computers.

Finite Element Alternating Method - The finite element alternating method (FEAM) has been developed at Georgia Institute of Technology through the FAA Center of Excellence in Computational Modeling for Aircraft Structures. The FEAM is used to obtain the stress-intensity factor solutions for a crack in a finite body, for both two-dimensional and three-dimensional configurations. The FEAM is also capable of modeling material plasticity.

In the alternating method as applied to a crack in a finite solid, two types of solutions are required. First, a general analytical solution for an embedded elliptical crack in an infinite body subjected to arbitrary crack face tractions is required. The complete solution for an embedded crack in an infinite solid and subjected to arbitrary crack face tractions was rederived by Nishioka and Atluri [7] from the general solution developed by Vijaykumar and Atluri [6]. Nishioka and Atluri [7] also derived the general procedure to evaluate the necessary elliptic integrals in the generalized solution for the elliptic crack. In the solution, the pressure on the crack surface is expressed as a polynomial as:

$$p_\alpha = \sum_{i=0}^{1} \sum_{j=0}^{1} \sum_{m=0}^{M} \sum_{n=0}^{m} A_{\alpha,m-n,n}^{(i,j)} x_1^{2m-2n+i} x_2^{2n+j} \tag{1}$$

Second, a numerical scheme (in this case, the finite element method) is needed to solve for the stresses in the uncracked finite body.

In the finite element alternating method, the finite element method is used to analyze the uncracked finite body under the given external loads. The geometry of the uncracked body is identical to that of the cracked body except for the crack itself. Since the crack is not explicitly

modeled, nonzero stresses are calculated at the location of the actual crack. These fictitious stresses must be removed in order to create the traction-free crack surface existing in the actual problem. The analytical solution for an infinite body with an embedded elliptical crack is known for an arbitrary distribution of tractions on the crack face. To create the stress-free crack face, a polynomial function for the inverse of these fictitious stresses is determined using a least square fit and applied to the infinite cracked body. The stresses on the external surfaces of the finite body due to the applied loads on the crack faces are calculated. The inverse of these stresses is applied as an external load on the finite uncracked body. This addition to the external loads again creates fictitious stresses at the crack location which must be removed to obtain the stress-free crack faces in the actual configuration. All steps in the iteration are repeated until the stresses on the crack surface become negligible. The overall stress-intensity factor solution is obtained by adding the stress-intensity factor solutions for all the iterations. The process is illustrated schematically in figure 1.

It is necessary that the finite element mesh used to describe the uncracked body be refined enough to accurately characterize the stress distribution in the uncracked body. If the geometry and applied loading of the configuration are relatively simple, not as many elements are required since the stress state is not complex. However, if either the geometry or the loading is such that there are significant stress gradients in the uncracked body, then a greater number of elements will be required. It is also necessary that there be enough refinement in the region of the crack to accurately fit a polynomial distribution to the fictitious stresses on the crack face. An example of a typical mesh used to calculate stress-intensity factors for cracks at countersunk rivet holes [8] is shown in figure 2. The refined mesh normally needed in a standard finite element analysis in not required in the FEAM, thus resulting in considerable savings in the time required to generate the mesh as well saving in the computational time for the solution itself.

To extend the finite element alternating method to the analysis of nonlinear materials, Nikishkov and Atluri [9] developed a new algorithm for the solution of elastic-plastic fracture mechanics problems. An analytical solution for an elastic crack, with arbitrary crack-face loading, was used inside an initial stress iterative procedure. The iteration processes of the alternating method and

the initial stress method are performed simultaneously. The elastic-plastic finite element alternating method (EPFEAM) algorithm was modified by Park and Atluri [10] for the analysis of configurations with multiple cracks by using the analytical solution of collinear multiple cracks with arbitrary crack surface tractions.

The T* Fracture Criterion

To use the EPFEAM to predict the residual strength of aircraft structures, it is necessary to develop a crack growth criteria. The T*-integral [11] has been incorporated into the EPFEAM by Pyo, Okada, and Atluri [12-14] and Wang, Brust, and Atluri [15]. The T*-integral is defined on a small contour around the crack tip, as shown in figure 3. This integral parameter is known to be effective not only for stationary problems but also for fast propagating and stablely propagating cracks in nonlinear material [11]. For quasi-static problems, the T*-integral is defined as

$$\boldsymbol{T}_{\varepsilon}^{*} = \oint_{\Gamma_{\varepsilon}} \left(\boldsymbol{W} \, \boldsymbol{n}_1 - \boldsymbol{t}_1 \frac{\partial \boldsymbol{u}_1}{\partial \boldsymbol{x}_1} \right) d\,\Gamma_{\varepsilon} \tag{2}$$

In the case of a propagating crack, the integral contour Γ_ε moves along with the crack tip. The T*-integral can be interpreted, for a suitably small value of ε, as a scalar parameter that quantifies the severity of the crack-tip fields. The T*-integral depends only on the near tip deformation field, so that in the case of self-similar stable crack propagation, the T*-integral should become a constant value. For stationary cracks subjected to monotonic loading, T^*_ε is identical to the J integral [16].

Verification of the T* Fracture Criterion

An extensive test program is underway for methodology validation, as well as to develop a basic understanding of failure mechanisms. To use the T*-integral as a fracture parameter, a T*-resistance curve must first be developed. The T*-resistance curve is obtained by simulating the load versus crack extension (P-Δa) curve computationally for a panel with a single crack. Using

this one T*-resistance curve as the fracture criterion, predictions can be made for any other cracked geometry of interest, including multiple site damage.

The load versus crack growth data from tests conducted at the National Institute of Standards and Technology (NIST) were used to determine the T*-resistance curve. A series of large-scale, thin-sheet 2024-T3 aluminum panels were tested in uniaxial tension. A total of ten panels were tested; three with a single center crack, seven with different multiple site damage crack patterns. Details on the test program can be found in Ref. 17. Figure 4 shows the T*-resistance curves that were generated for one of the center cracked panels with a width $W = 90$ inches, a crack length, $2a = 8$ inches, and thickness, $t = 0.4$ inch. The resistance curve for $\varepsilon = 0.087$ inch was fitted with an equation and was used for predictions of the panels with multiple cracks. A discussion of the meaning of the different ε path size definitions and their physical significance in presented in Ref. 15. The T*-resistance curve for any of the other values of ε could have been used and the predictions would be identical [15].

Figure 5, which shows the equation for the T*-resistance curve, shows the analytical predictions compared to the experimental data for a test panel with multiple cracks. The panel contained a center crack 14 inches in length and three smaller cracks on each side of the main crack. The analytic predictions compare very well with the experimental results. The predictions for both the linkup loads and the maximum load are nearly identical to the test data. Similar results were predicted for the other test results [15].

The experimental and analytical results presented here and in Ref. 15 verify the T* fracture criterion for predicting the residual strength of flat aluminum panels with a crack under uniaxial tension loading. Further analysis is planned to fully verify the criterion for predicting residual strength of complex stiffened structures.

Probabilistic WFD Model

A probabilistic method will be developed to describe the uncertainties in the prediction of widespread fatigue damage (WFD). Some of the sources of uncertainty include initial size and distribution of flaws, residual stresses, aircraft usage, loads, environmental conditions, rivet

interference, joint flexibility, hole misalignment, maintenance procedures, damage mechanisms, inspection and repair procedures, and variability in material properties. This should result in a practical life and risk assessment methodology, consistent with transport aircraft design and maintenance practices, that is easy to apply and that applies useful information for decision making. Features which shall be integrated in the methodology include:

- different damage processes: crack initiation, crack growth, crack/ligament instability
- different damage drivers: cyclic stresses, aggressive environments, and their interactions
- complex structural/WFD geometries: component assemblies, stress concentrators, crack interactions, etc.
- complex loads: service load spectra, residual stresses, etc.
- different criteria for failure: current residual strength, remaining crack growth life, current structural reliability
- different analysis approaches: deterministic (safety factor) and probabilistic (risk assessment)

TECHNOLOGY TRANSFER

An important element in the FAA research program is the technology transfer phase. In order for any tool to be effective it must be used, and used properly, by its intended audience. It is pointless to develop the most accurate, efficient methodology if it is not used. In order to enhance the transfer of this methodology to its end users, both within the FAA and in industry, software tools, based on the analytical methodologies, will be developed. These tools will be user-friendly and computationally efficient, and appropriate documentation and training will be provided. To insure that the methodology does meet the needs of the end users, industry will be involved in the development as much as possible.

SUMMARY

The FAA is developing an integrated widespread fatigue damage (WFD) risk assessment methodology. The methodology will be developed in a modular approach to take advantage of a

variety of tools already under development. The methodology will contain both deterministic and probabilistic analytical methods. It will be able to analyze both two- and three-dimensional geometries and nonlinear material and geometries. This methodology, once developed, will provide the means to quantitatively evaluate the structural integrity of aircraft structures, considering the effects of WFD. This tool will provide assistance to both the FAA and industry in assessing the continued airworthiness of the commercial fleet. The FAA is also conducting experiments to validate the analysis methods used in the integrated methodology as a first step in the technology validation and industry acceptance processes. The FAA is working closely with industry to enhance the transfer of this technology to the end users.

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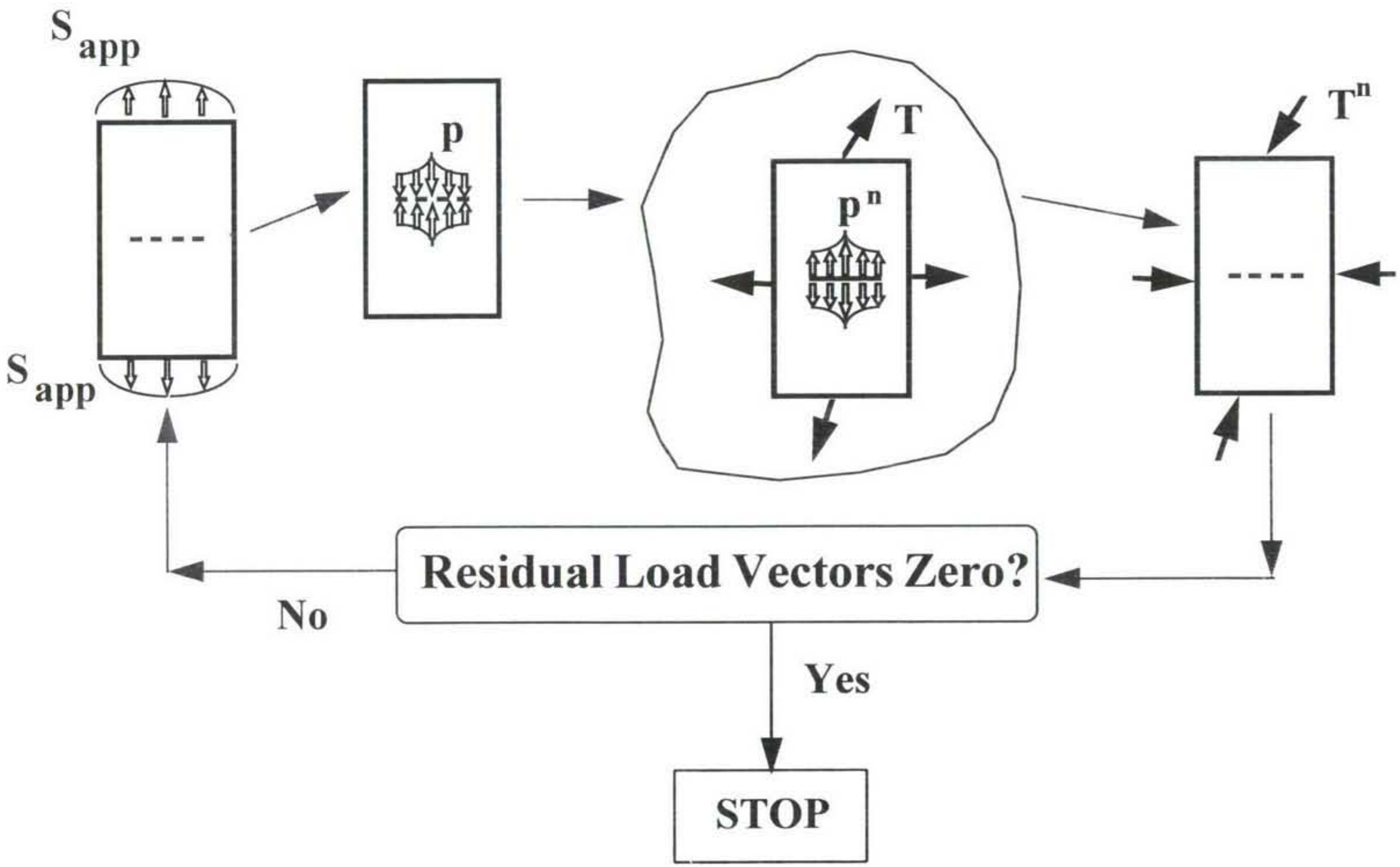

Figure 1 - Finite element alternating method (FEAM) flow diagram

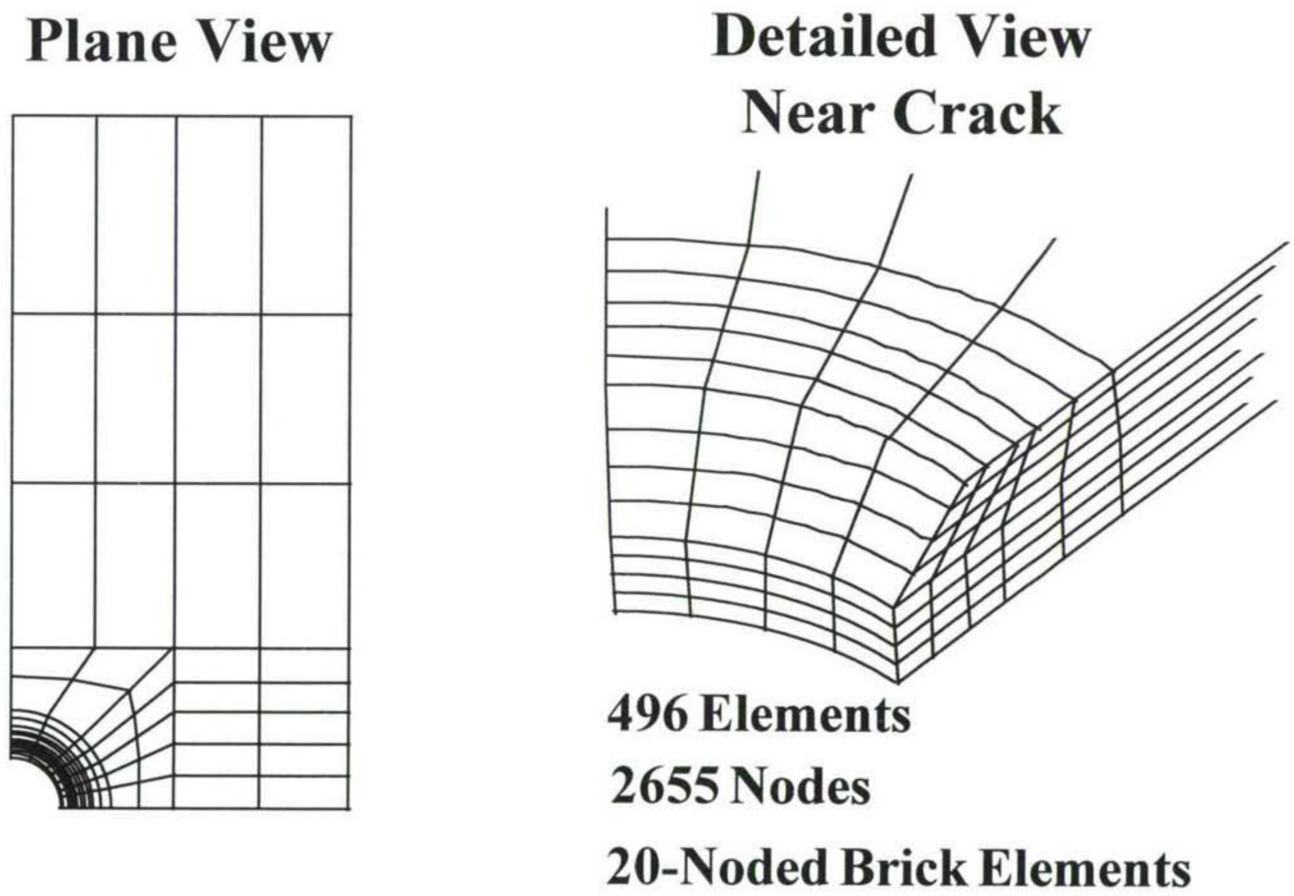

Figure 2 - Typical mesh for finite element alternating method

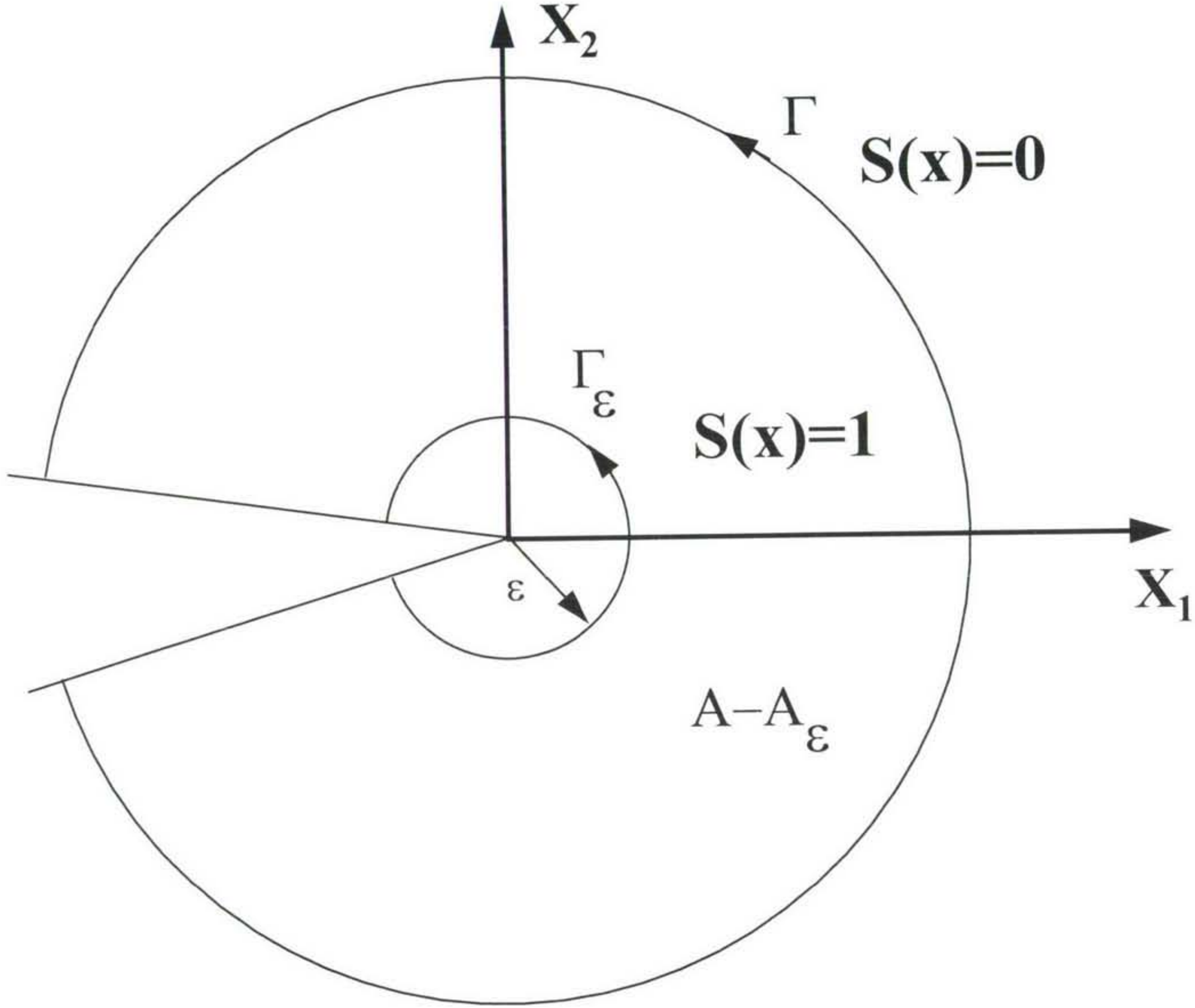

Figure 3 - Contour used to define T*-integral

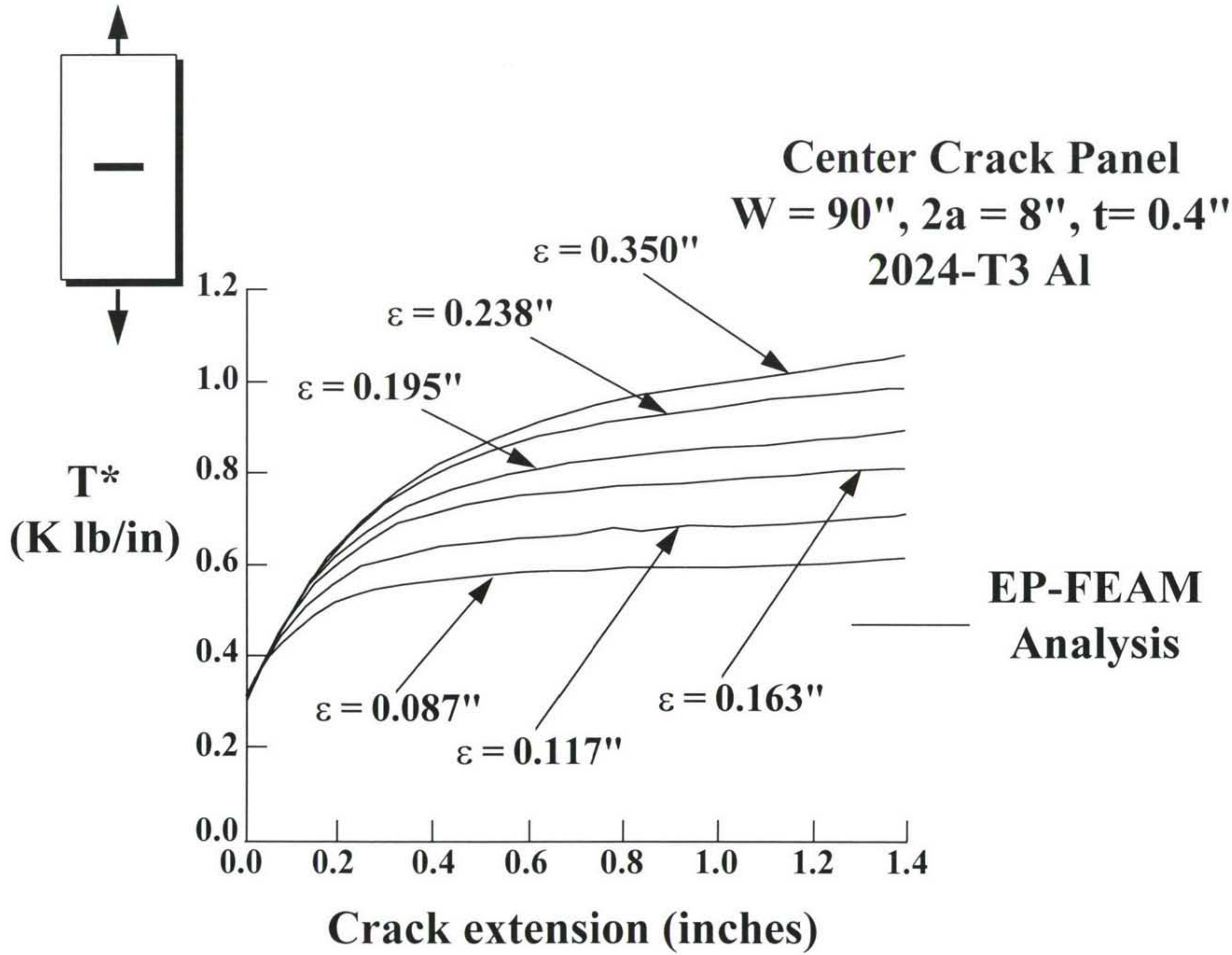

Figure 4 - Definition of T*-resistance curve

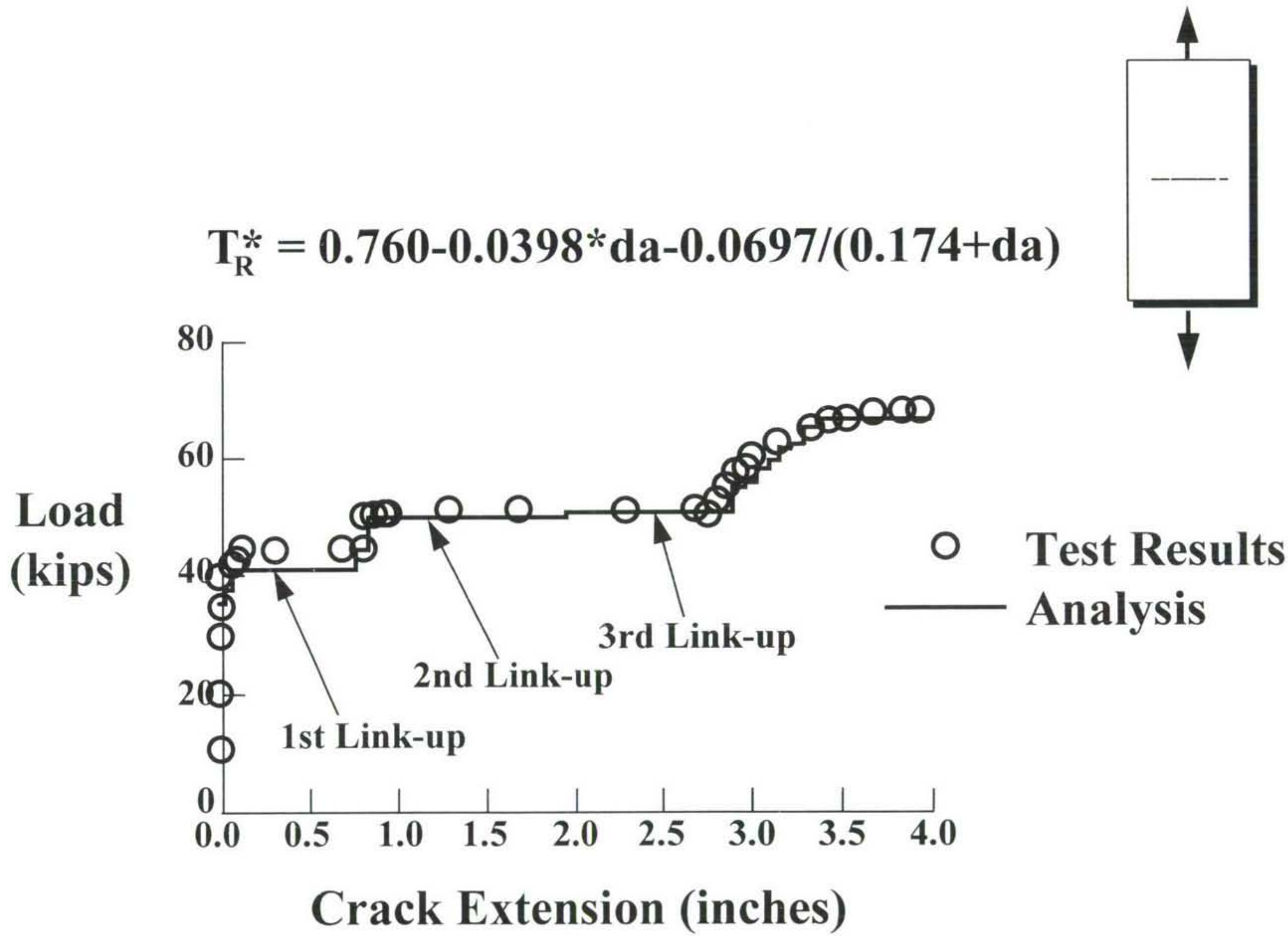

Figure 5 - Analytical prediction compared to experimental results for crack growth and residual strength of large-scale aluminum panel

Development of Advanced Structural Analysis Methodologies for Predicting Widespread Fatigue Damage in Aircraft Structures

Charles E. Harris
James H. Starnes, Jr.
James C. Newman, Jr.
Research and Technology Group
NASA Langley Research Center
Hampton, VA 23681

ABSTRACT

NASA is developing a "tool box" that includes a number of advanced structural analysis computer codes which, taken together, represent the comprehensive fracture mechanics capability required to predict the onset of widespread fatigue damage. These structural analysis tools have complementary and specialized capabilities ranging from a finite element-based stress-analysis code for two- and three-dimensional built-up structures with cracks to a fatigue and fracture analysis code that uses stress-intensity factors and material-property data found in "look-up" tables or from equations. NASA is conducting critical experiments necessary to verify the predictive capabilities of the codes, and these tests represent a first step in the technology validation and industry acceptance processes. NASA has established cooperative programs with aircraft manufacturers to facilitate the comprehensive transfer of this technology by making these advanced structural analysis codes available to industry.

NOMENCLATURE

a	= crack half length
a_i	= initial crack half length
B	= plate thickness
CTOA	= crack tip opening angle
CTOD	= crack tip opening displacement
d_r	= spacing of MSD cracks
L_i	= total initial crack length for MSD
L_r	= length of small MSD cracks
MSD	= multiple site damage (cracks)
M	= bending moment
N_i	= stress resultants as designated by the subscript
p	= internal pressure
P_i	= frame and stringer loads as designated by the subscript
S	= applied far-field stress
S_n	= net-section stress
T	= torsional load
V	= vertical shear load
W	= plate width
σ_{ys}	= yield stress
σ_u	= ultimate tensile strength

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Airframe Structural Integrity Program (NASIP) was initiated in 1990 after extensive consultations with the U.S. airframe manufacturers, airline operators, and the Federal Aviation Administration (FAA). The objective of the program is to develop advanced technology that can be used by the U.S. industry to maintain economically the aging commercial transport fleet while insuring continuous airworthiness. The program is a formal cooperative program with the U.S. aircraft industry and is part of the U.S. Government Strategic Plan for Aging Aircraft Research that includes FAA and NASA activities. While the development of cost-effective nondestructive inspection technology is a major part of the NASA Airframe Structural Integrity Program, the present paper only addresses the development of a structural integrity analysis methodology for predicting the onset of widespread fatigue damage.

The ability to predict analytically the onset of widespread fatigue damage in fuselage structures requires methodologies that predict fatigue crack initiation, crack growth, and residual strength. Mechanics-based analysis methodologies are highly desirable because differences in aircraft service histories can be addressed explicitly and rigorously by analyzing different types of aircraft and specific aircraft within a given type. Each aircraft manufacturer has developed mature in-house durability and damage-tolerance design and analysis methodologies that are based on their product development history. To enhance these existing successful methodologies, NASA has adopted the concept of developing an analytical "tool box" that includes a number of advanced structural analysis computer codes which, taken together, represent the comprehensive fracture mechanics capability required to predict the onset of widespread fatigue damage. The structural analysis tools have complementary and specialized capabilities ranging from a nonlinear finite element-based stress-analysis code for two- and three-dimensional built-up structures with cracks to a fatigue and fracture analysis code that uses stress-intensity factors and material-property data found in "look-up" tables or from equations. The development of these advanced structural analysis methodologies has been guided by the physical evidence of the fatigue process assembled from detailed teardown examinations of actual aircraft structure. In addition, NASA is conducting critical experiments necessary to verify the predictive capability of these codes and to provide the basis for any further methodology refinements that may be required. The NASA experiments are essential for analytical methods development and verification, but represent only a first step in the technology validation and industry acceptance processes. Each industry user of this advanced methodology must conduct an assessment of the technology, conduct an independent verification, and determine the appropriate integration of the new structural analysis methodologies into their existing in-house practices. NASA has established cooperative programs with U.S. aircraft manufacturers to facilitate this comprehensive transfer of the technology by making these advanced methodologies available to industry.

A detailed description of the methodologies under development is presented in the present paper. A brief description of the structural analysis computer codes in the NASA tool box is given in the paper. Beta-site testing of the various structural analysis codes is currently underway and the

technology that is being transferred to industry is highlighted. The status of the analytical residual-strength prediction methodology is discussed in the context of an application to a generic stiffened aluminum thin-shell structure fabricated by a riveted-skin construction method. The status of the experimental verification of the methodology is also discussed.

STRUCTURAL ANALYSIS COMPUTER CODES FOR STRUCTURAL INTEGRITY

The NASA tool box outlined in Table 1 contains several structural analysis computer codes that have been developed to meet specific specialized engineering requirements. Even though the data in Table 1 suggest that the codes may have overlapping capabilities, each code has unique capabilities that are required to address specific durability and damage-tolerance issues for a wide variety of engineering applications. The determination of the number of aircraft service hours that is related to the onset of widespread fatigue damage includes analyses for crack initiation, fatigue crack growth, and residual strength. Therefore, the computational capability required to predict analytically the onset of widespread fatigue damage must be able to represent a wide range of crack sizes from the material (microscale) level to the global structural-scale level. NASA studies indicate that the fatigue crack behavior in aircraft structure can be represented conveniently by the following three analysis scales: small three-dimensional cracks at the microscale level; through-the-thickness two-dimensional cracks at the local structural level; and long cracks at the global structural level. The computational requirements for each of these three analysis scales are described in the following paragraphs.

The first analysis scale and corresponding computational capability represents the fracture mechanics of small cracks that exhibit three-dimensional crack-growth behavior. The existence and growth of these small cracks do not affect the global structural deformation states or internal load distributions. Examples of these cracks are surface and corner cracks that initiate at the edges of plates or at holes. Stress-intensity-factor solutions are typically obtained from computational procedures such as the finite element analysis method. The ZIP3D computer code [1] has been developed to model three-dimensional crack configurations and to calculate the corresponding stress-intensity factors. This finite element analysis code uses an eight-node element and can be used to analyze stationary and growing cracks under cyclic elastic-plastic

conditions, including the effects of crack closure. The FRANC3D code [2] also has solid modeling capabilities for three-dimensional geometries based on the boundary element method. For those crack configurations and general loading conditions that may occur for various structural components, weighting-function solutions are being developed from the numerical results of parametric studies. These weighting-function equations are particularly useful because the stress-intensity-factor solutions can be obtained from a stress analysis of the uncracked structure. Stress-intensity-factor solutions are currently being generated for cracks that initiate at countersunk rivet holes. Loading conditions include interference-fit stresses, clamp-up stresses, and loads transferred through a rivet. These stress-intensity-factor solutions may then be used as input data for the FASTRAN II code [3] to predict fatigue-crack growth. The FASTRAN II code is based on the mechanics of plasticity-induced crack closure. The effects of prior loading history on fatigue behavior, such as crack-growth retardation and acceleration, are computed on a cycle-by-cycle basis. The code will predict the growth of cracks exhibiting the "small-crack effect" as well as two- and three-dimensional cracks exhibiting the classical Paris-law crack-growth behavior. The code has been shown to be especially effective for predicting fatigue-crack-growth behavior in structures subjected to aircraft spectrum loads. The ZIP3D, FRANC3D, and FASTRAN II codes operate efficiently on engineering workstations, and FASTRAN II also operates on personal computers.

The second analysis scale and corresponding computational capability represent the fracture mechanics of fatigue cracks that extend through the thickness of a skin or stiffener and are no longer three-dimensional in their crack-growth behavior. Two-dimensional analyses are typically quite adequate for predicting crack growth. However, accurate modeling of structural details is required to provide high-fidelity results for the local stresses in a structure so that the fracture-mechanics calculations will be accurate. The FRANC2D finite element analysis code [4] has been developed for the analysis of two-dimensional planar structures and the STAGS (STructural Analysis of General Shells) nonlinear shell analysis code [5] has been developed for general shell structures. The FRANC2D code, developed by Cornell University, is a user-friendly engineering analysis code with pre- and post-processing capabilities especially developed for fracture-mechanics problems. The code operates on UNIX-based engineering

workstations with X-Windows graphics and is interactive and menu driven. A unique capability of the code is the ability to predict non-self-similar crack-growth behavior. An automatic adaptive remeshing capability allows an engineer to obtain a history of the stress-intensity factors for any number of cracks in the structure and for any arbitrary crack-growth trajectory. The STAGS finite element code [5], developed by Lockheed Palo Alto Research Laboratory, provides the capability to model any general shell structure and has both geometric and material nonlinear analysis capabilities. STAGS is particularly well suited for analyzing shells that have structural features such as frames, stiffeners, and cutouts. The code uses the Riks arc-length projection method and computes large displacements and rotations at the element level. The code has been developed especially for nonlinear stability and strength analyses. Both FRANC2D and STAGS can calculate the history of the stress-intensity factors for a growing crack that are compatible with FASTRAN II so that fatigue-crack growth analyses may be performed. Other crack growth models may also be used. STAGS and FRANC2D operate on engineering workstations and mainframe computers.

The third analysis scale and corresponding computational capability represent structures with long cracks that change the internal structural load distribution, that exhibit behavior strongly affected by structural details, and that affect the residual strength of the structure. In addition, the fracture mechanics of ductile materials such as 2024-T3 aluminum alloy often requires an elastic-plastic stress-analysis capability that predicts stable tearing and fracture. Furthermore, nonlinear geometric effects, such as crack bulging in shell structures, also significantly affect residual-strength predictions. All of these complexities are present in a fuselage shell structure and must be represented in a residual-strength analysis of the fuselage. NASA has developed a unique capability that integrates the fracture topology modeling capabilities of FRANC3D with the general shell analysis capabilities of STAGS into an integrated FRANC3D/STAGS analysis procedure [6]. The automatic adaptive remeshing capability of FRANC3D and the geometric nonlinear stress-analysis capability of STAGS provides the analysis basis required to predict the crack-growth, crack-turning, and crack-arrest behavior exhibited by pressurized shell structures in damage-tolerance tests. Such a residual-strength analysis capability for a fuselage shell structure requires a suitable fracture criterion. Current plans include implementing the critical

crack tip opening-angle criterion (CTOA), the T* criterion, and the K-R curve criterion into the STAGS analysis code for predicting the residual strength of shell structures. This capability is described in greater detail in the following sections of this paper. For simple two-dimensional plane-stress or plane-strain fracture mechanics problems, the ZIP2D special-purpose finite element code [7] has proven to be very accurate and computationally efficient. The integrated FRANC3D/STAGS analysis procedure currently operates on high-level workstations or on mainframe computers, and ZIP2D operates on workstations.

Several of the advanced durability and damage-tolerance analysis capabilities developed in the NASA program will also be implemented in the NASGRO analysis code [8]. NASGRO is a general-purpose damage-tolerance analysis code being developed by NASA Johnson Space Center. The code is based on fracture mechanics principles and may be used to compute stress-intensity factors, fatigue-crack growth, critical crack sizes, and the limit of safe life. An extensive library of stress-intensity factors may be used with NASGRO or solutions may be obtained from a boundary element analysis capability using the FADD analysis code [9]. NASGRO also has an extensive material property library which includes most aluminum alloys, titanium alloys, and steels commonly used in the aerospace industry. Fatigue-crack growth may be computed from a crack-closure mechanics model or from one of several empirical models commonly used by industry. NASGRO is used extensively throughout the aerospace industry. FADD was developed at the University of Texas and uses the distributed-dislocation method to compute stress-intensity factors. This approach combines a highly accurate stress-intensity factor analysis with the modeling simplicity of the boundary element analysis method. FADD is also available in a stand-alone version and is currently being tested by industry at beta-site locations. NASGRO operates on engineering workstations and personal computers. FADD is also available as a stand-alone code and operates on personal computers.

RESIDUAL-STRENGTH ANALYSIS METHODOLOGY

The structural analysis computer codes under development in the NASA Airframe Structural Integrity Program are being integrated into an analytical methodology for predicting the residual strength of a fuselage structure with one or more cracks. The analytical prediction of the residual

strength of a complex built-up shell structure, such as a fuselage, requires the integration of a ductile fracture criterion, a fracture-mechanics analysis, and a detailed stress analysis of the structure. The crack tip opening-angle (CTOA) criterion has been experimentally verified to be a valid fracture criterion for mode I stress states in thin and moderately thick (0.5 inch thick or less) aluminum alloys. The CTOA criterion has been demonstrated to be valid for predicting the link-up of a long lead crack with small fatigue cracks ahead of the advancing lead crack. This fracture criterion has been implemented into the STAGS geometric and material nonlinear finite element-based shell analysis code to provide an integrated structural-integrity analysis methodology. The capability to model a growing crack that may extend in a non-self-similar direction has been added to the STAGS code along with an automated mesh refinement and adaptive remeshing procedure. The topological description of the growing crack is provided by the FRANC3D fracture mechanics code. The geometric nonlinear behavior of a stiffened fuselage shell is currently under study for internal pressure loads combined with fuselage body loads that produce tension, compression, and shear loads in the shell. A detailed description of this capability is described in the following paragraphs.

The CTOA Fracture Criterion

The critical crack tip opening-angle (CTOA), or equivalently, the crack tip opening-displacement (CTOD) fracture criterion is a "local" approach to characterizing fracture. In contrast, the J-integral or J-R curve criterion is based on global deformations and has been found to be specimen and crack-size dependent for structures with large amounts of stable tearing. The constant CTOA (or CTOD) criterion has been used to predict the variations in J-R curves due to differences in crack sizes and specimen types. Therefore, a local crack tip displacement is a more fundamental fracture parameter than the J-integral representation for local strain-controlled fracture processes such as stable tearing and void coalescence.

Stable crack growth in metallic materials has been studied extensively using elastic-plastic finite element methods [10-17]. These studies were conducted to examine various local and global fracture criteria such as the CTOA or CTOD criteria, the crack tip stress or strain criteria, the strain-energy release-rate criterion, the J-integral criterion and the tearing modulus criterion. It

was shown by de Koning [12] that the CTOA is nearly constant from crack-growth initiation to failure in an aluminum alloy. Shih, et al., [15] and Kanninen, et al., [16] showed that the CTOA at crack-growth initiation is apparently larger than the value needed for stable crack growth in fracture analyses of both steel and aluminum alloys. Brocks and Yuan [18] and Demofunti and Rizzi [19] found that CTOA is nearly constant for various materials and thicknesses after a small amount of crack growth. Newman [17] used the critical CTOD values obtained from compact tension specimens to predict failure loads to within 10 percent of the test results for several other crack configurations for two aluminum alloys and a ductile steel. Paleebut [20] also measured the CTOD at the initiation of stable tearing in aluminum alloys and these measured values of CTOD agree well with Newman's numerical results [17]. The results of tests conducted by Hellman and Schwalbe [21] show good correlation between the CTOD values measured at the initial fatigue-crack tip location for stable tearing in a variety of specimen types. More recently, Newman, Dawicke, Sutton, and Bigelow [22] used a high-resolution microscope with a video recording system to measure the CTOA during stable crack growth in 2024-T3 aluminum. These test results show that the CTOA is constant for both center-cracked panels and compact tension specimens over a wide range of crack- extension lengths after a small (approximately one sheet thickness) amount of crack growth.

Simple plastic-zone models that are based on linear-elastic stress-intensity factors can be adjusted to fit experimental data and then used to predict crack link-up for relatively simple structural geometries. While these methods predict the correct trends in crack link-up behavior, they may be difficult to apply to analyses of complex structural details that are characteristic of a fuselage structure. The CTOA criterion can be effectively implemented into a finite element analysis code provided that the code has elastic-plastic deformation and crack-growth simulation capabilities. These capabilities exist in the STAGS geometric and material nonlinear shell analysis code, but analyses of large-scale problems must currently be conducted on a high-performance mainframe computer. After thorough experimental verification of the residual-strength analysis methodology, it is anticipated that the methodology can be simplified by taking advantage of appropriate engineering approximations.

Verification of the CTOA Fracture Criterion Using Flat-Panel Test Data

An extensive test program has been conducted to interrogate experimentally the characteristics of the CTOA criterion and to establish its validity as a fracture criterion for thin-sheet 2024-T3 aluminum. A schematic of the four basic flat-panel geometries used to verify the elastic-plastic finite element code and the CTOA criterion for mode I fracture is shown in Figure 1. The blunt-notch panel was used to verify the finite element analysis code used to compute plastic deformation fields and large displacements. Measurements of far-field displacements and the local displacements inside the open holes at the ends of the crack were accurately predicted by the finite element analysis for large-scale plastic deformations.

The center-crack and three-hole-crack panels were used to measure the load (or far-field applied stress) as a function of crack extension and the CTOA during stable tearing. Because the tests were conducted at a specified controlled displacement rate, crack extension was measured well beyond the maximum load observed during the test. Stable tearing was quite extensive in the three-hole-crack specimen because the crack driving force is reduced as the crack approaches the two large open holes in a manner that is similar to the behavior of cracks in stiffened panels. A high-resolution long-focal-length microscope was used to record the stable-tearing results. The microscope image was videotaped, digitized, and recorded in a computer file. The tearing event was then analyzed on a frame-by-frame basis and the critical opening angle was measured throughout the fracture event. A typical CTOA measurement is shown in Figure 2. As can be seen in the figure, the opening angle is relatively insensitive to the length over which the angle is measured. The results of a three-hole-crack panel test are given in Figure 3. After an initial transition region, the CTOA is constant throughout the stable-tearing process. The initial transition region is caused by a three-dimensional effect that occurs as the crack tunnels and transitions from flat- to slant-crack growth. Over 63 mm (2.5 in.) of stable tearing was recorded and the CTOA values were nearly constant. Measurements such as these were also made for center-crack and three-hole-crack panels of various widths, crack lengths, and sheet thicknesses ranging from 1.02 mm (0.040 in.) to 2.29 mm (0.090 in.). Also, measurements of the CTOA were obtained for compact tension specimens. In all cases, the measured CTOA was

approximately 6.0° for cracks oriented in the LT direction of the sheet and 5.1° for cracks oriented in the TL direction, where L designates the principal rolling direction of the sheet and T designates the direction transverse to the principal rolling direction. A complete description of these test results is given in reference 22.

An elastic-plastic finite element analysis was conducted for every test-panel configuration reported in reference 22. A typical stress-analysis result for a center-crack panel is shown in Figure 4. The analysis assumes plane-stress conditions and the applied stress as a function of crack extension is predicted using a CTOA value of 6.0°. Test results for three sheet thicknesses are shown in the figure. As can be seen in the figure, there is virtually no thickness effect on the test results for this range of sheet thicknesses. The finite element analysis accurately predicted the maximum applied stress and the crack extension before and after the maximum value of the test load had been applied. A complete description of the finite element analysis code and the analysis method along with more results can be found in reference 22.

To verify further the CTOA fracture criterion, a series of panels with multiple-site cracks (MSD) was also tested to determine the conditions leading to crack link-up. Under sponsorship by the FAA, the Foster-Miller Company [23] conducted a number of fracture tests on 508 mm (20.0 in.) wide panels with one-, three-, five-, and seven-crack configurations. Each crack configuration has a long center crack with small MSD cracks symmetrically located ahead of the long center crack. NASA conducted a finite element analysis of each panel. The analytical and experimental results for a panel with a 305 mm. (12.0 in.) long center crack and two 12.60 mm (0.50 in.) long cracks on both sides of the center crack with a 25.4 mm (1.0 in.) long ligament between the small cracks are given in Figure 5. By using a CTOA value of 5.1°, the finite element analysis accurately predicted the applied stress S_1 for the first crack link-up, the maximum stress S_2 sustained by the panel, and the applied stress S_3 for the second crack link-up. Catastrophic failure of the panel occurred after the second crack link-up. Descriptions of the complete Foster-Miller test results and analyses using other fracture criteria are given in reference 23 and the results of additional analyses using the CTOA criterion are given in reference 22.

A summary comparing several test results and the finite element analysis predictions for the panels with multi-site damage or MSD is given in Figure 6. For convenience, the applied far-field stress S has been divided by the yield stress σ_{ys} of 2024-T3 aluminum alloy. Also shown for comparison is the applied stress at which the ligament between the cracks or the edge of the specimen was fully yielded. The long center cracks for the four examples shown in the figure are of different lengths. The CTOA fracture criterion and the elastic-plastic finite element analysis accurately predicted the failure stresses for all flat-panel test results. Also, the results in the figure indicate that the ligament between the cracks for the MSD crack configurations is fully yielded at a stress level well below the applied stress level at crack link-up. This comparison suggests that a simple fracture criterion such as the "ligament net-section stress equal to yield stress" criterion should be used with some degree of caution. The effects of MSD on the residual strength of a 1.016 m (40.0 in.) wide flat panel with a 0.356 m (14.0 in.) long center crack is illustrated by the analytical results shown in Figure 7. The crack lengths and spacings are plotted along the abscissa of the figure and the applied far-field stress is plotted along the ordinate. The dashed lines represent the crack-extension behavior of the panel with only a single long lead crack of the indicated lengths. The solid line shows the crack-extension behavior due to the MSD cracks ahead of the long lead cracks. There is a reduction in the residual strength of the panel due the presence of MSD. In this example, both the long lead crack and the first small crack grew toward each other prior to crack link-up.

The experimental and analytical results presented herein verify the CTOA fracture criterion for predicting the residual strength of flat panels with cracks undergoing mode I fracture behavior. Further testing is required to verify the criterion for predicting the residual strength of complex stiffened shell structures. The CTOA criterion must be extended to mixed-mode loading conditions. Also, numerical procedures for crack extension under mixed-mode loading conditions must be implemented into an elastic-plastic shell analysis code. And finally, the ability to predict crack trajectories accurately and to model curved crack growth must be developed. The next section describes the stiffened shell structural analysis methodology being developed for analyzing a fuselage structure and to predict its residual strength accurately.

Development of a Geometric Nonlinear Finite Element Shell Analysis Code

The STAGS nonlinear finite element analysis code is being modified to include the capability of conducting crack-growth and residual-strength analyses for stiffened fuselage shell structures subjected to combined internal pressure and mechanical loads. STAGS was originally developed to predict the strength, stability and nonlinear response of non-axisymmetric or general shells and includes analyses for both geometric and material nonlinear behavior. The nonlinear solution algorithm used in STAGS is based on Newton's method and includes both the modified and full versions of Newton's method. Large rotations are represented by a co-rotational algorithm at the element level and the Riks arc-length projection method is used to integrate past limit points. The finite element library includes nonlinear beam, plate, and shell elements. Complex stiffened shell structures can be modeled to include as many finite elements as required to represent accurately the response of each structural member in the stiffened shell of interest. The computational efficiency of the code allows nonlinear analyses of models with over 100,000 degrees of freedom to be conducted in a reasonable amount of computer time. Both self-similar and non-self-similar crack- growth prediction capabilities have been added to STAGS for predicting crack growth in a shell that is in a nonlinear equilibrium state. The crack-growth analysis used in FRANC3D/STAGS is based on a virtual crack extension analysis that calculates the strain energy release rate for nonlinear shells with mixed-mode crack growth including shell wall bending. A load relaxation capability is used to represent the local load redistribution that occurs as a crack grows in the shell and Newton's method is used to maintain nonlinear equilibrium as the crack propagates. Nonlinear adaptive mesh refinement is used to determine the necessary finite element model changes as the crack propagates.

The general strategy for developing the nonlinear structural analysis methodology for predicting residual strength of stiffened shells with cracks is shown in Figure 8. Large-scale global models of a stiffened fuselage shell of interest are developed and nonlinear analyses are conducted to determine the internal load distribution and general response of the shell as shown in the upper left of the figure. A hierarchical modeling approach is used to provide more highly refined local models which are developed based on the global model results. The local models provide the

higher-fidelity solutions that are necessary to predict stress and displacement gradients near the crack discontinuity in the shell as shown in the upper right of the figure. Several local models are generated as required and analyzed to provide the detailed stress and deflection results necessary to predict crack growth and residual strength for any structural detail feature such as the longitudinal lap splice shown in the lower right of the figure. Selected curved stiffened panels and stiffened shells will be tested to provide experimental verification of the STAGS nonlinear shell analysis capability.

Nonlinear Behavior of Stiffened Shells With Damage

An example of the hierarchical modeling strategy for nonlinear stiffened shell analysis is shown in Figure 9. The nonlinear hoop stress and radial deflection results for the global shell model of a frame and stringer stiffened aluminum shell are shown on the left of the figure. The shell has a longitudinal crack at the top of the fuselage and is loaded by 55.2 KPa (8 psi) of internal pressure. The longitudinal crack in the skin is next to a stiffener and the frame at the crack location is also broken. A curved stiffened panel model was developed with five frames and five stringers to generate the 36-skin-bay local model as shown in the upper right of the figure. This model provides more detailed stress- and deflection-gradient results near the cracked region as shown in the figure. The results shown are for a 0.508 m (20.0 in.) long skin crack with the center of the crack at the broken frame. The frames are located at the dark circumferential regions in the figure. The boundary conditions for this local model are based on the results of the global model analysis and both equilibrium and compatibility with the nonlinear global shell solution are maintained at the panel boundaries. A more refined stiffened panel model was developed with two frames and three stringers to generate the six-skin-bay local model shown in the lower right of the figure. The hoop stress and radial deflection results shown are for a 1.016 m (40.0 in.) long crack that has grown to the frames on either side of the broken frame. The boundary conditions for this more refined local model are based on the results of the 36-skin-bay stiffened panel model and both equilibrium and compatibility with the nonlinear 36-skin-bay panel solution are maintained at the six-skin-bay panel boundaries. This hierarchical modeling and analysis approach provides the high-fidelity nonlinear stress- and deflection-gradient results

needed to represent the shell behavior near the crack to the level of accuracy required to predict crack growth and residual strength accurately.

This hierarchical modeling approach has been used to determine the effects of combined internal pressure and mechanical loads on the response of a stiffened shell with a skin crack at the top of the shell. The crack is 0.254 m (10.0 in.) long initially and is located midway between the two stringers at the top of the shell and midway between two frames. The shell is subjected to the following three loading conditions: internal pressure only, internal pressure plus a down-bending moment, and internal pressure plus an up-bending moment. The axial stress resultants from the nonlinear analyses for these three loading conditions are shown in Figure 10. The axial stress resultants for the global model with internal pressure only are shown in the upper part of the figure and these results indicate that the value of the axial stress resultant is approximately 17.5 KN/m (100 lb/in.) except in the immediate vicinity of the crack where the value of the axial stress resultant is approximately 52.5 KN/m (300 lb/in.). The axial stress resultants for the global model with the internal-pressure and down-bending loads are shown in the lower left of the figure and these results indicate that the values of the axial stress resultants are approximately 52.5 KN/m (300 lb/in.) in tension at the top of the shell and approximately 52.5 KN/m (300 lb/in.) in compression at the bottom of the shell. The axial stress resultants for the global model with the internal-pressure and up-bending loads are shown in the lower right of the figure and these results indicate that the values of the axial stress resultants are approximately 52.5 KN/m (300 lb/in.) in compression at the top of the shell except in the immediate vicinity of the crack and approximately 52.5 KN/M (300 lb/in.) in tension at the bottom of the shell. The results for the local six-bay panel analyses for these three loading conditions are shown in Figure 11 for 0.254-, 0.381-, 0.508-m- (10-, 15- and 20-in.-) long cracks. The results for the internal-pressure-only load case is shown at the top of the figure and indicate that the axial stress resultant values are approximately 14.0 KN/m (80 lb/in.) in compression at the frames and are approximately 70.0 KN/m (400 lb/in.) in tension along the crack boundary. The extent of these high values of axial stress resultants grows locally as the crack grows in length. The results for the internal-pressure plus down-bending load case is shown in the middle of the figure and indicate that the axial stress resultant values are approximately 31.5 KN/m (180 lb/in.) in tension at the frames

and are approximately 70.0 KN/m (400 lb/in.) in tension along the crack boundary. The results for the internal-pressure plus up-bending load case are shown at the bottom of the figure and indicate that the axial stress resultant values are approximately 61.3 KN/m (350 lb/in.) in compression at the frames and are approximately 70.0 KN/m (400 lb/in.) in tension along the crack boundary. These results indicate that the complex local nonlinear behavior of the shell causes very different results for the three loading conditions. The effects of these differences on the mode I strain-energy release rate for the shell are shown in Figure 12 for the three loading conditions. The strain-energy release-rate results for increasing crack lengths are represented by the filled circles for the internal-pressure-only load case, by the filled triangles for the internal-pressure plus down-bending load case, and by the filled squares for the internal-pressure plus up-bending load case. These results indicate that the axial tension stress resultant at the crack associated with the down-bending load case decreases the strain-energy release rate by approximately 11 percent compared to the internal-pressure-only load case. The results also indicate that the axial compression stress resultant at the crack associated with the up-bending load case increases the strain-energy release rate by approximately 14 percent compared to the internal-pressure-only load case. These results suggest that the nonlinear coupling between the radial deflections and the in-plane stress resultants near the crack have a significant effect on the crack-growth and residual-strength characteristics of stiffened shell structures with longitudinal cracks.

SUMMARY

NASA is developing a "tool box" that includes a number of advanced structural analysis computer codes which, taken together, represent the comprehensive fracture mechanics capability required to predict the onset of widespread fatigue damage. These structural analysis tools have complementary and specialized capabilities ranging from a finite element-based stress-analysis code for two- and three-dimensional built-up structures with cracks to a fatigue and fracture analysis code that uses stress-intensity factors and material-property data found in "look-up" tables or from equations. NASA is also conducting critical experiments to verify the predictive capabilities of the analysis codes and these tests represent a first step in the

technology-validation and industry-acceptance processes. NASA has established cooperative programs with aircraft manufacturers to facilitate the comprehensive transfer of this technology by making these advanced structural analysis methodologies available to industry. Beta-site testing of the structural analysis codes is well underway and several of these codes have already been integrated into industry's durability and damage-tolerance engineering practices.

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Table 1 NASIP Computer Codes

Capability \ Codes	FADD*	FRANC2D	ZIP2D	FASTRAN II	STAGS	FRANC3D/STAGS	FRANC3D*	ZIP3D	NASGRO*
Plane Stress/Strain	X	X	X	X				X	
Axisymmetry		X			X			X	
Plate Bending	UD	UD			X	X			X
Thin Shell					X	X			
3D Solid	UD				UD		X	X	
Straight Cracks	X	X	X	X	X	X	X	X	X
Curving (nonplaner) Cracks	X	X				X	X		UD
Layered Structure		UD			X	X		X	
Contact		X			X	X		X	
Interface		X			UD				
Elasto-Plastic		UD	X		X	X		X	
Crack Closure/Variable Amplitude			X	X				X	UD
Anisotropy	UD	X			X	X			
Residual Strength Analysis		UD	X		UD	UD		X	
Graphical Interface	X	X				X	X		
Life Prediction				X					X
Mesh Generation	X	X				X	X		
K vs. A History	X	X			X	X	X		

*FADD is also implemented into NASGRO and FRANC3D
UD -- under development

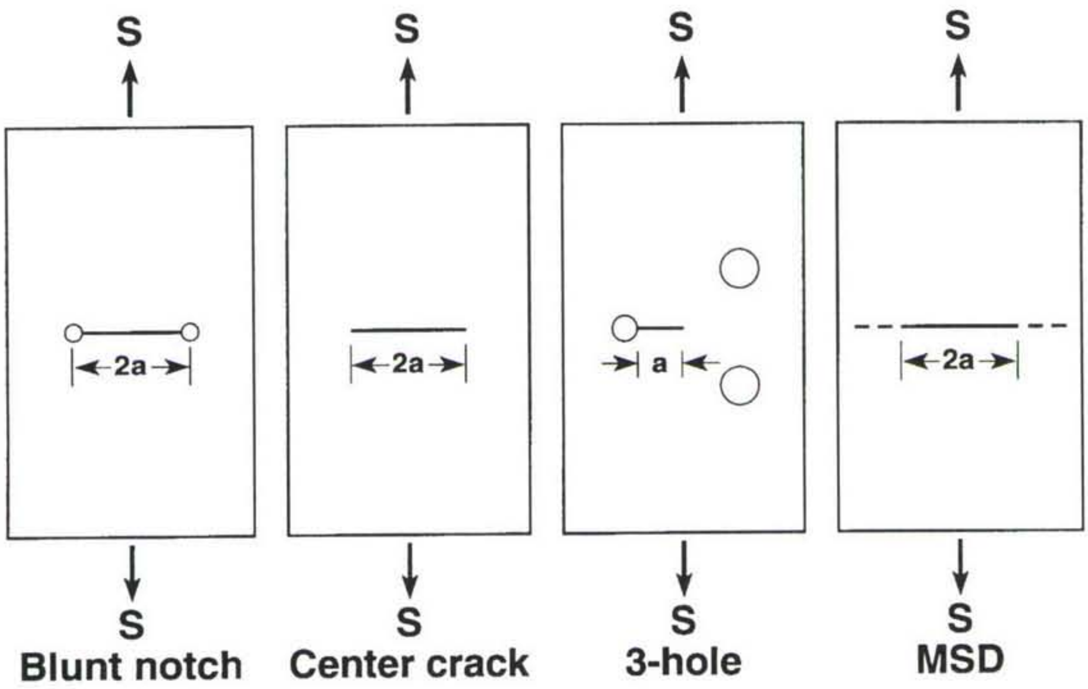


Figure 1. Fracture specimens for residual strength.

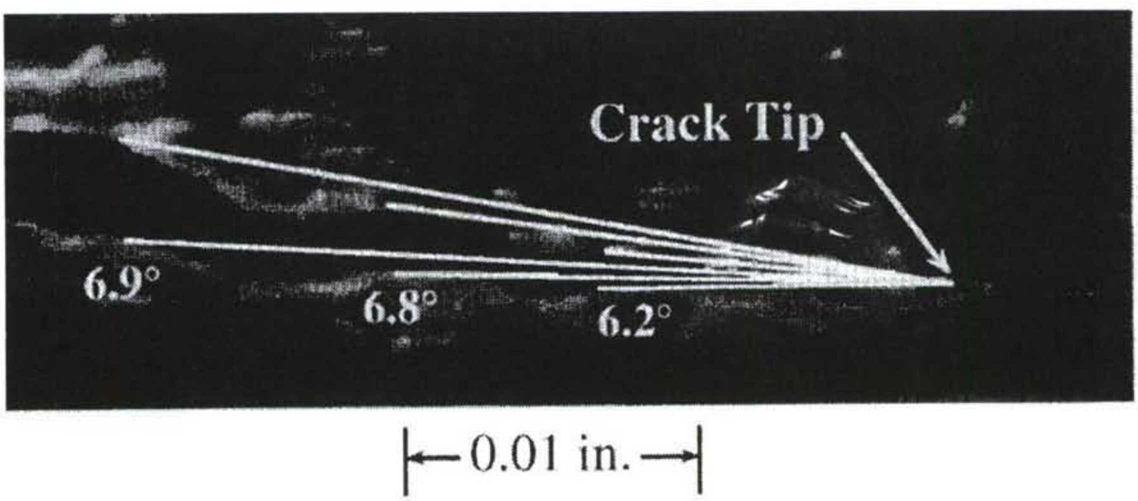


Figure 2. Crack tip opening angle (CTOA) measurements.

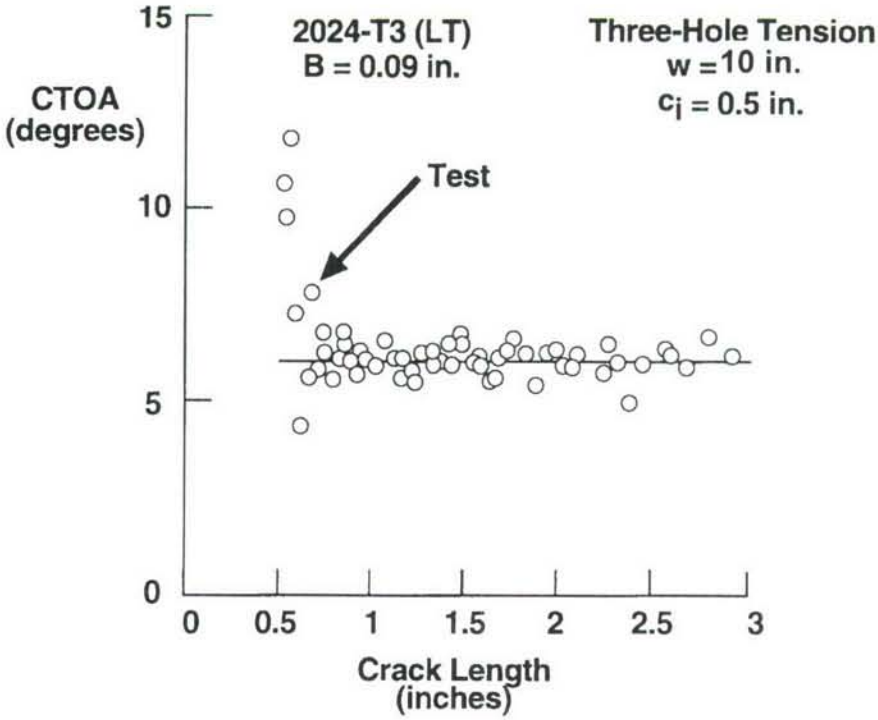


Figure 3. Experimental measurements of CTOA.

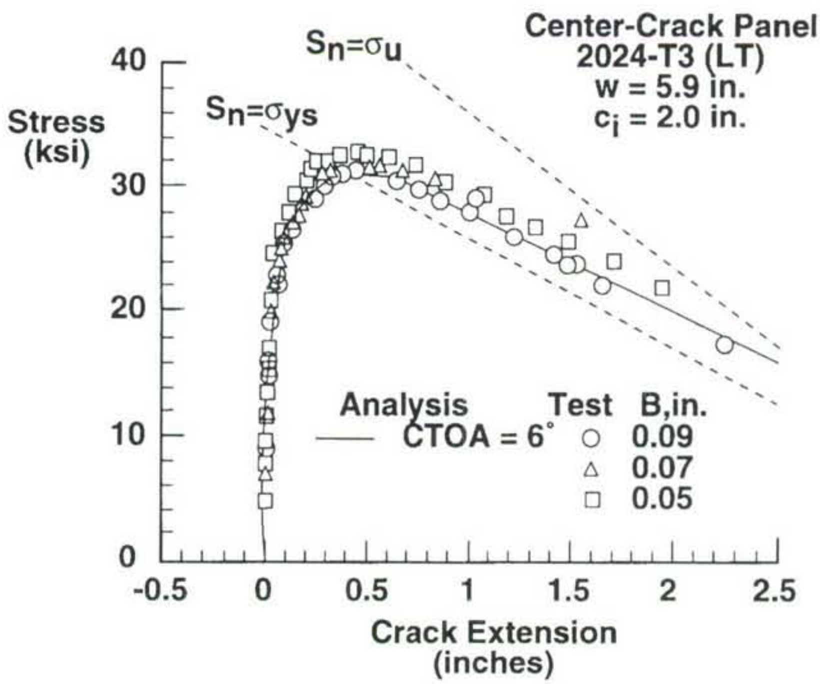


Figure 4. Effects of specimen thickness on crack extension.

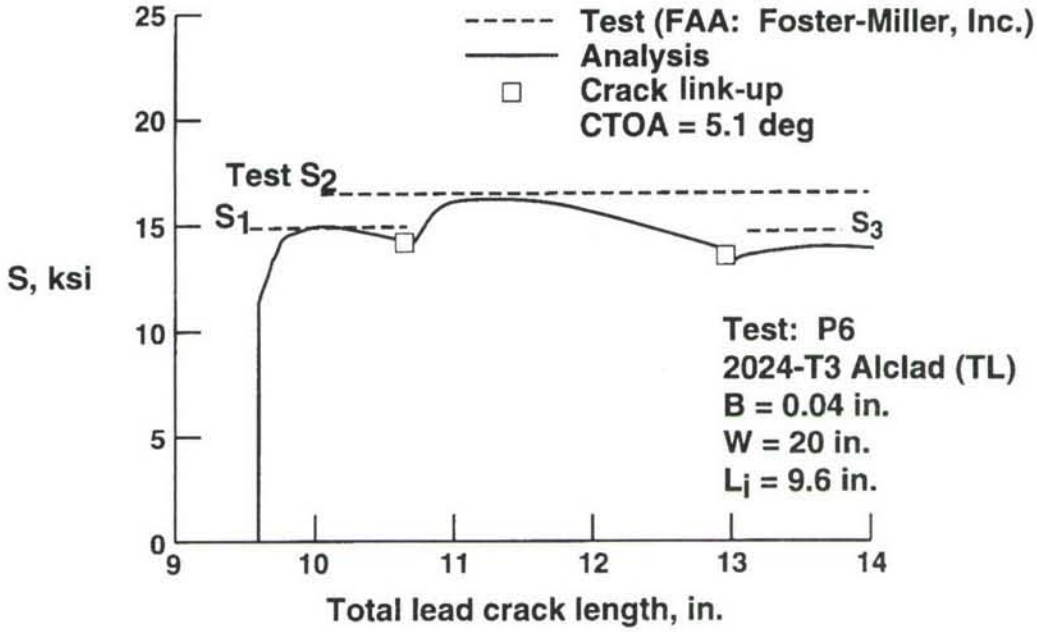


Figure 5. Residual strength of panel with long lead crack and two MSD cracks.

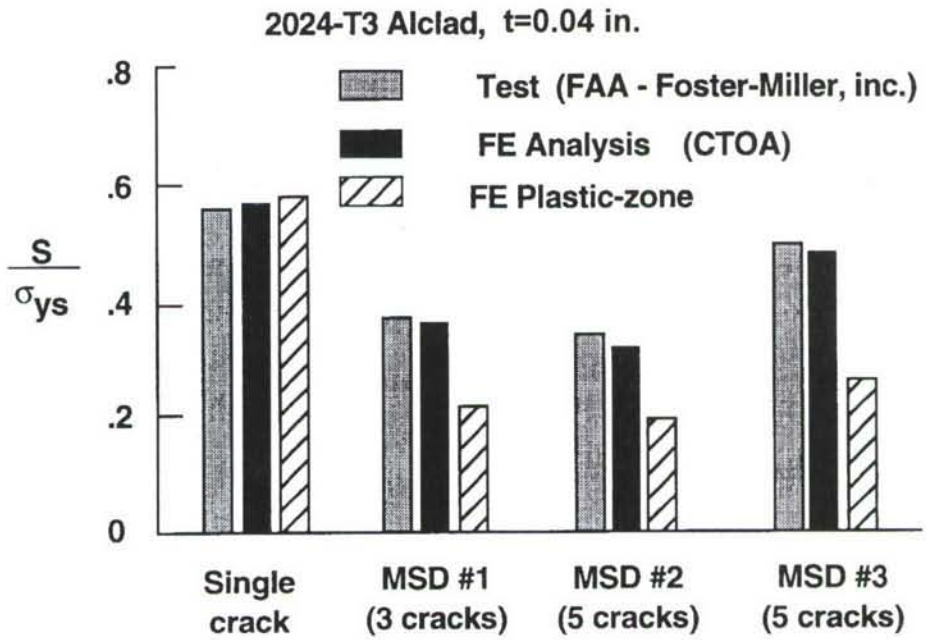


Figure 6. Comparison of test and analysis for single crack and MSD configurations.

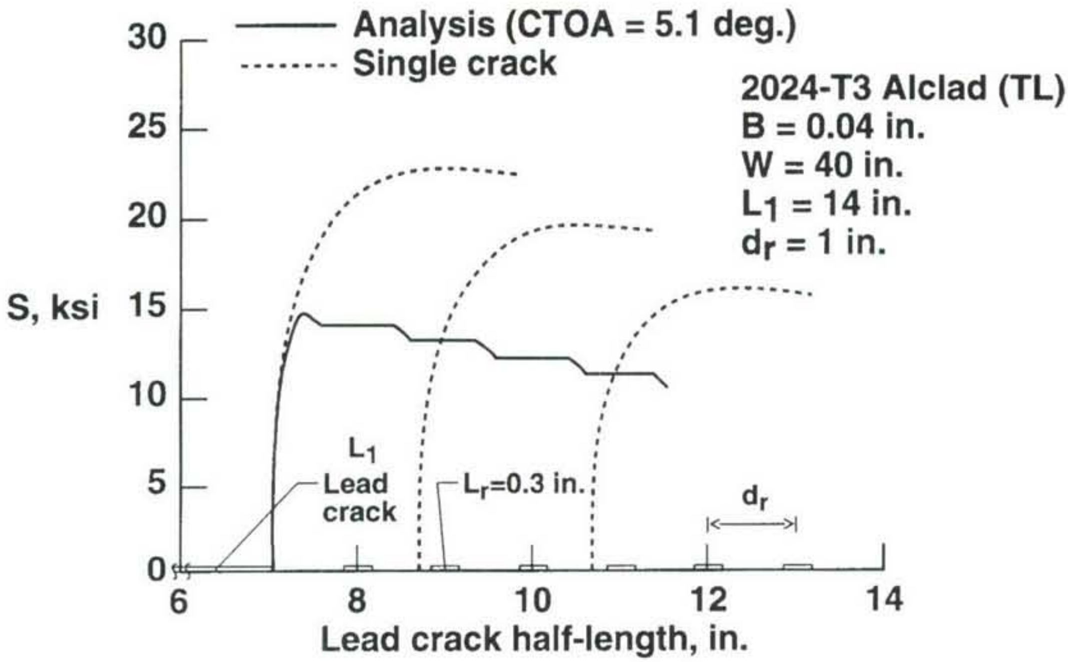


Figure 7. Effect of MSD on residual strength.

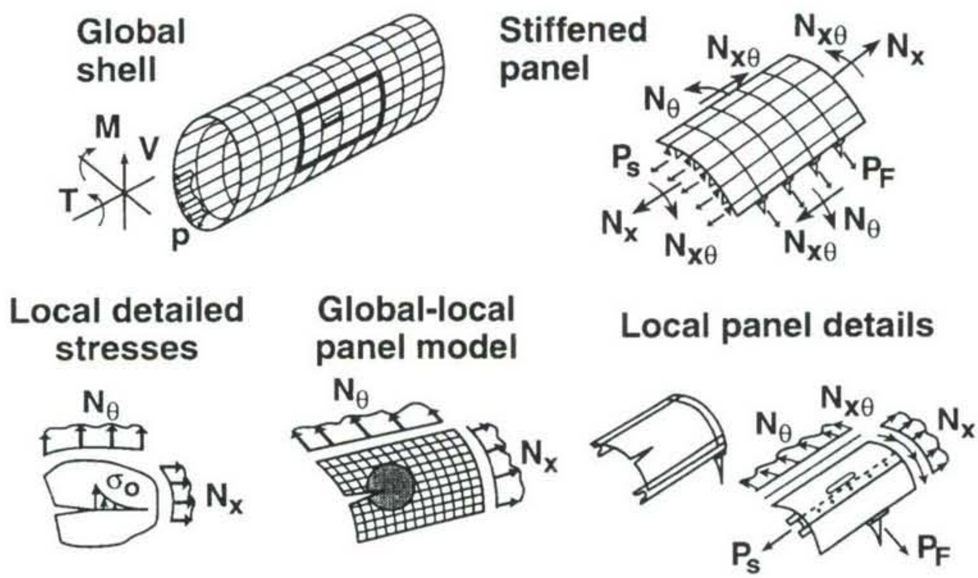


Figure 8. Hierarchical nonlinear stiffened shell models.

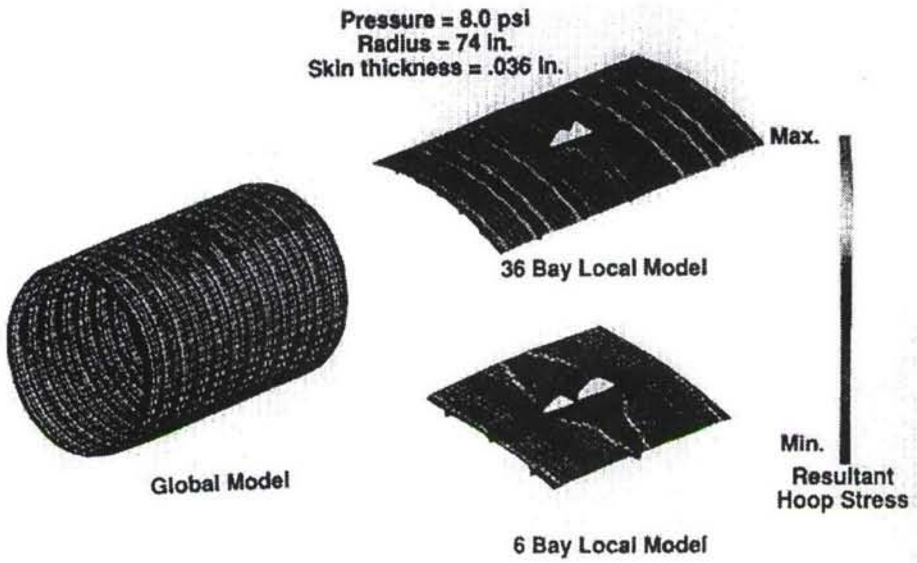


Figure 9. Analysis of stiffened aluminum fuselage shell with 20-in.-longitudinal skin crack and broken frame.

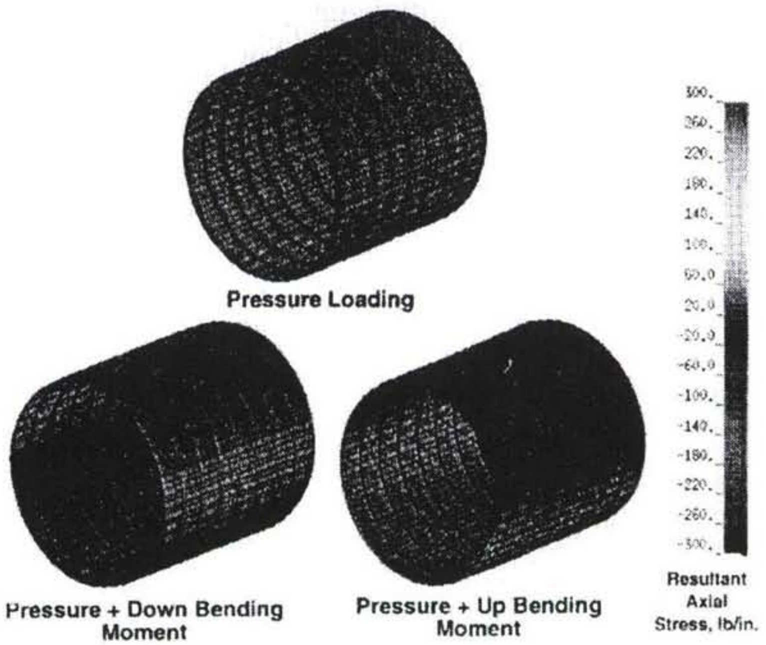


Figure 10. Global model of stiffened aluminum fuselage shell model with a 10-in.-longitudinal skin crack.

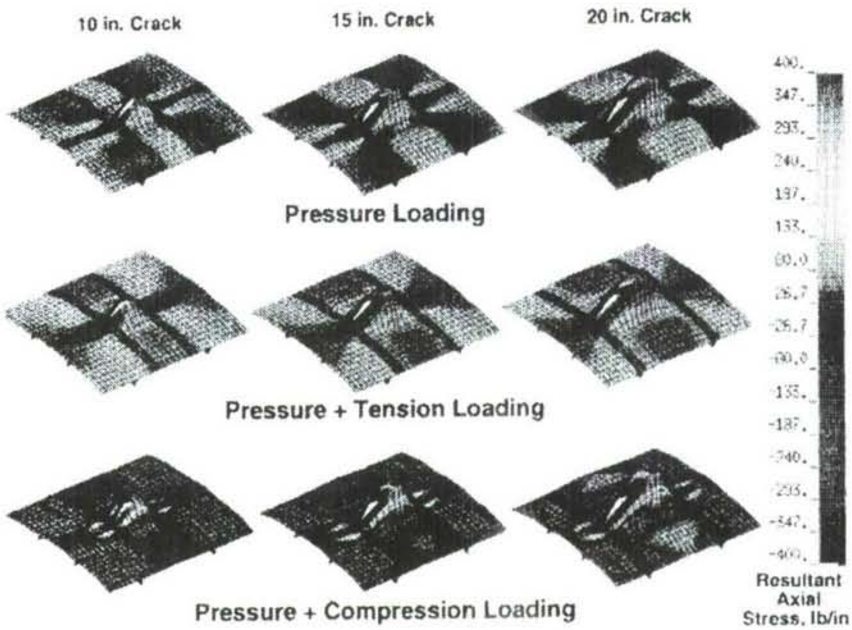


Figure 11. Two-bay by three-bay stiffened aluminum fuselage shell model with a skin crack.

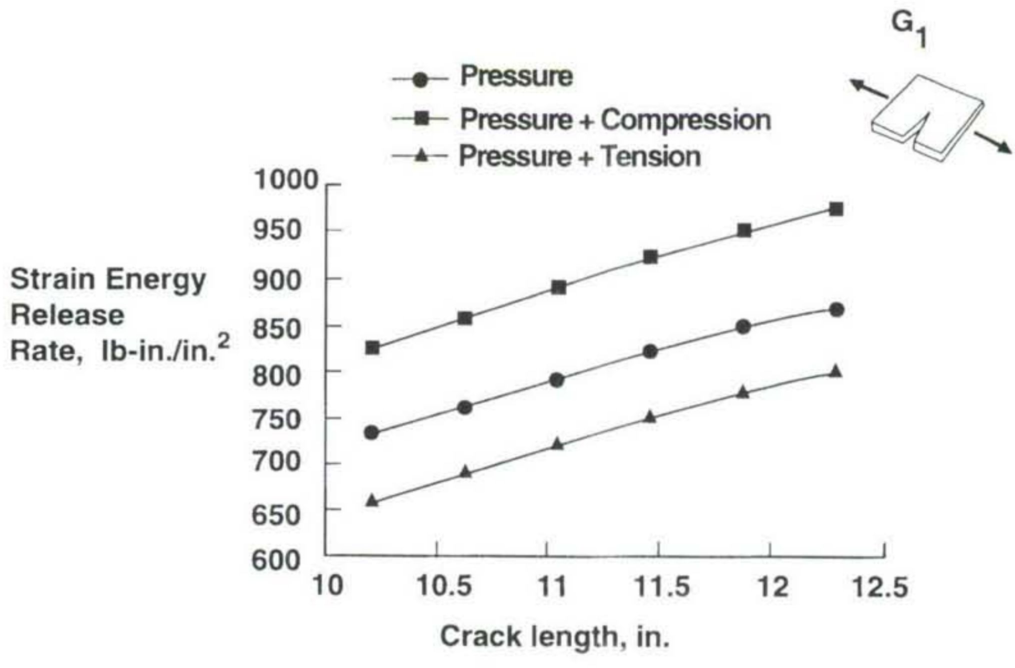


Figure 12. Two-bay by three-bay stiffened aluminum fuselage shell model.

McDONNELL DOUGLAS APPLICATION OF WFD METHODOLOGY TECHNOLOGY TRANSFER

John J. Tracy and Jin Yu
McDonnell Douglas Aerospace
Amos Hoggard
Douglas Aircraft Company

SUMMARY

Both the FAA Tech Center and the NASA Langley Research Center have made significant investments in the development of new technology for the assessment of widespread fatigue damage (WFD). The challenge at hand is to integrate this technology into the day-to-day design and analysis activities at the airframe manufacturers. McDonnell Douglas Corporation has ongoing efforts intended to transition the WFD activities into the corporation. The approach used to transfer technology is based on an integrated industry/government program consisting of frequent technology interchange meetings, technology tool training courses, on-site evaluations, technology validation testing, iterative feedback on tool performance, and subsequent modification and re-evaluation. The key to successful technology development and technology transfer is the close involvement of the airframe manufacturer during all phases of the program. This approach includes the joint prioritization of potential technology development tasks between the government and industrial partners. Most importantly, the approach uses the airframe manufacturers to provide the final validation of the methodology through analysis and testing of appropriate structural configurations which can be witnessed and validated be the local FAA Aircraft Certification Office.

INTRODUCTION

Even the smallest multisite damage (MSD) cracking can substantially reduce the residual strength capability for which an aircraft was certified. The question at hand is to what extent is the originally certified damage tolerance capability reduced by the presence of MSD (Figure 1). To develop an understanding of this problem the FAA and NASA have developed multiple tools to analyze multisite damage under the global subject of aging aircraft. Within the McDonnell Douglas Corporation (MDC), the Advanced Transport Aircraft Development Division (ATAD)

has been chartered with assessing the FAA and NASA technology and transferring it to the aircraft production engineering environment at Douglas Aircraft Company (DAC). Key technology areas included crack initiation, flaw distribution, crack propagation, residual strength, and nondestructive inspection (NDI) methods (Figure 2).

TECHNOLOGY TRANSFER

Our approach to technology transfer is centered on the concept of joint technology development and cooperative research with the government partners. With this ongoing effort, technology is transferred through technology interchange meetings, on-site training courses, production readiness assessments, and technology validation testing. End-user involvement is an essential element of all technology development and transfer activities since the end users are the ones who understand best what requirements must be met by the developed technology. With respect to aircraft certification, the FAA has specific requirements for any newly developed analytical technique that the aircraft manufacturer would propose to use. Analysis must be demonstrated to be accurate or conservative relative to expected behavior. FAR 25.307(a) states that "..structural analysis may be used only if the structure conforms to that for which experience has shown this method to be reliable...". With respect to damage tolerance, FAR 25.571 (a)(1)(iii) requires "an analysis supported by test evidence." Analysis for predicting onset and behavior of WFD is no different. The analysis method must predict test behavior, failure modes, failure loads, and must be conservative.

To meet these requirements, a formal and significant certification process must be followed. The methodology user forms a contract with the FAA, which when completed, provides the basis for FAA acceptance of the methodology. The approval process involves the local FAA Aircraft Certification Office (ACO) for coordination and conformity assurance. An analysis verification plan is developed and submitted for approval which identifies the work to be done, investigation parameters, tests to be completed, proposed correlation means, and acceptable pass/failure criteria. The plan also proposes the schedule and FAA manpower commitments required to witness tests and review results.

Analysis areas identified by DAC and MDA for assessment include: local/global finite element analysis, load redistribution due to damage, crack tip stress intensity solutions for 2D and 3D cracks, multisite/multielement fatigue crack initiation and propagation, MSD linkup failure criteria, and residual strength of global structures. With respect to NASA developed WFD technology, MDC has initiated a memorandum of understanding (MOU) with NASA to jointly investigate WFD technology. Through this MOU, McDonnell Douglas is in the process of transitioning WFD tools and technology such as the FASTRAN crack propagation code, the FRANC2D and FRANC3D fracture mechanics codes, the STAGS finite element code for local/global analysis, and criteria such as the Crack Tip Opening Angle (CTOA). With respect to the FAA, McDonnell Douglas has begun initial investigations of criteria such as T* and tools such as the finite element alternating method (FEAM).

The majority of the technology transfer work to date has centered on the FASTRAN crack propagation code. FASTRAN has been and continues to be evaluated for transport aircraft usage through comparison with MDA in-house codes. Pre- and postprocessors have been created to reduce the analysis cycle time. A material and crack growth rate database has been created for DAC commonly used materials. Further validation through testing is currently being planned for 7050-T7361 aluminum plates. Test loads will include constant amplitude and compression dominated flight spectra.

Figure 3 shows the comparison of the FASTRAN crack closure model with the generalized Willenborg model and the general Willenborg model with compression cycles for a simple straight sided test coupon with a single crack. For constant amplitude cyclic loading with minimum to maximum stress ratio, R=0.0 and R=0.4, it can be seen that all three models predict the same structural life at stress levels below 25 ksi and some variation for higher stress levels. However for R = - 0.5, the three models give significantly different results even at the lowest stress levels. Figure 4 shows the comparison of the three models with respect to the effect of underloads and overloads. Large variations (almost an order of magnitude) in structural life are seen for the higher underload values.

APPLICATION IN WFD DEVELOPMENT

MDC is currently pursuing a cooperative program with the FAA and NASA to develop an integrated procedure for predicting the onset of WFD. The methodology will be validated by an extensive test program which will focus on the WFD prone structures to investigate the small-crack behavior, MSD growth and its interaction, linkup between lead crack and MSD, and the residual strength characteristics of WFD. Specimens representing critical fuselage structures in various sizes ranging from small coupons to a full-scale airplane will be tested. Each type of test specimen is designed for specific objectives which are briefly discussed below:

Coupon Tests -

The main purpose of these tests is to investigate small crack growth behavior and MSD formation along fasteners holes. Splice joint coupons of various configurations will be tested to establish a comprehensive database for analysis and prediction of WFD in the more complicated structure and stress field. Test results will also be used to validate stress intensity factors computed by the finite element alternating method FEAM and FRANC3D. The small-crack fatigue crack growth will be predicted using FASTRAN.

Panel Tests -

The test specimens will include skin-stringer flat panels and curved configurations representing a wide-body fuselage construction. The loading will be cyclic uniaxial or biaxial with or without cabin pressure. The purpose of these tests is to characterize MSD growth and to determine crack linkup criteria in the presence of WFD. Test results will be used to correlate predictions made by FEAM, FRANC2D/L and STAGS for crack tip stress distribution, and by FASTRAN for MSD growth. Experimental results for crack linkup will be correlated with prediction made by the T* and CTOA criteria.

DC-9 Fuselage Test -

A DC-9 fuselage will be utilized to investigate the WFD issue pertinent to narrow-body fuselage structure and to determine the characteristics of WFD in aging aircraft. The fuselage barrel will allow simulation of multiple MSD at selected components prone to WFD. The fuselage will be subjected to cyclic fatigue loading interspersed with limit load applied via pressurization of the fuselage cabin. The results from this test will be valuable in validating the integrated WFD methodology.

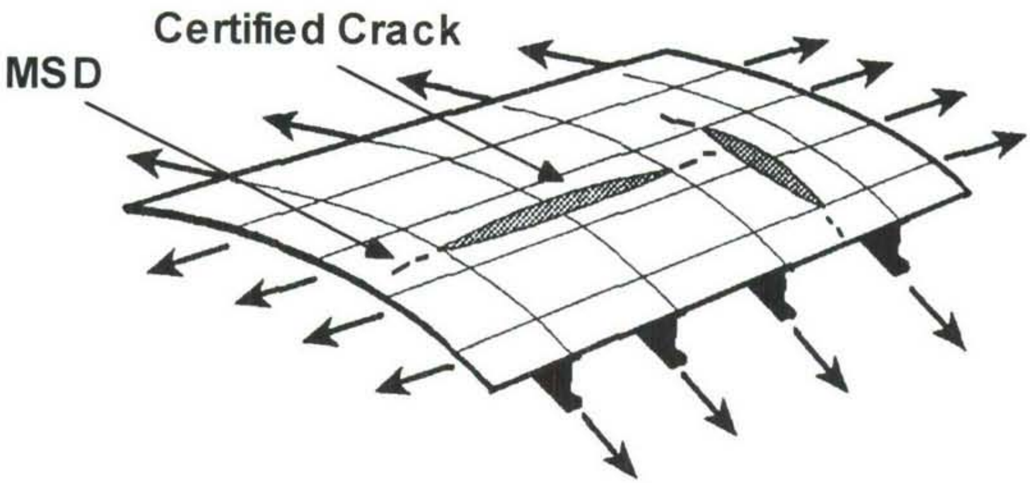


Figure 1. Multisite Damage Configuration

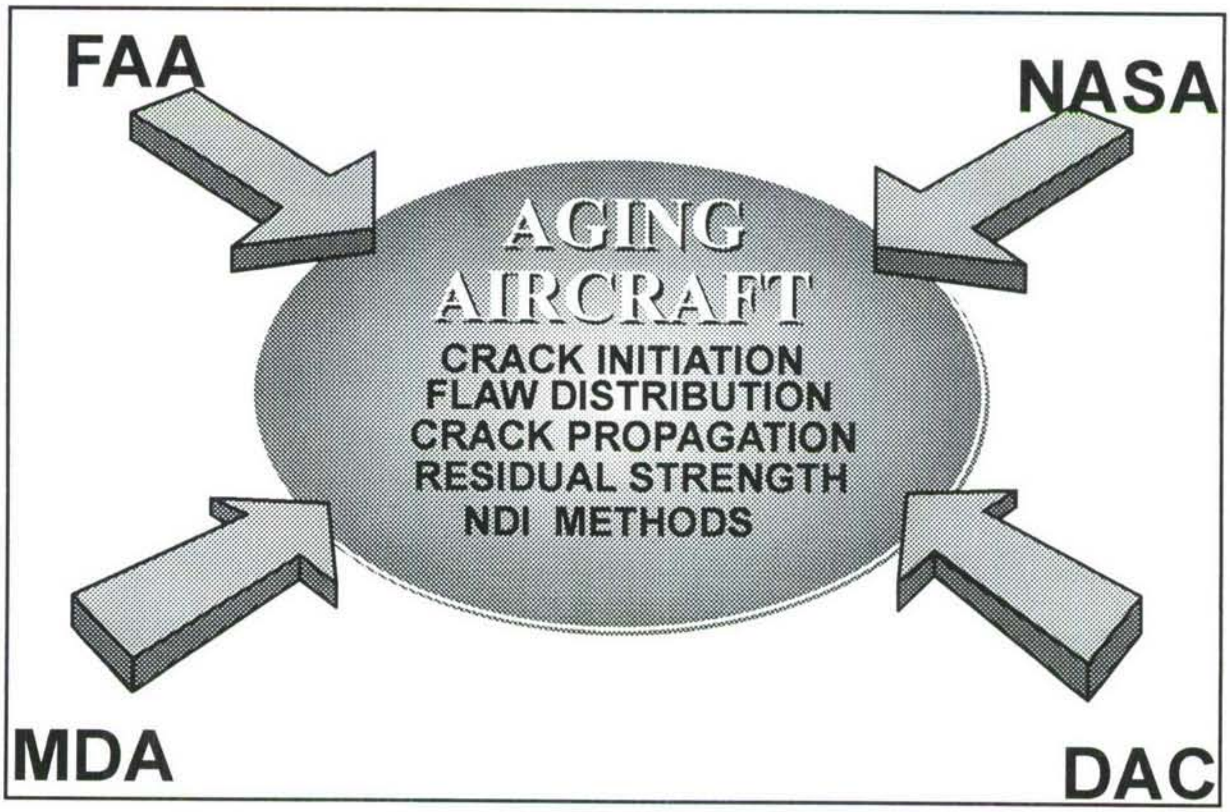


Figure 2. Government/Industry Focus on Aging Aircraft

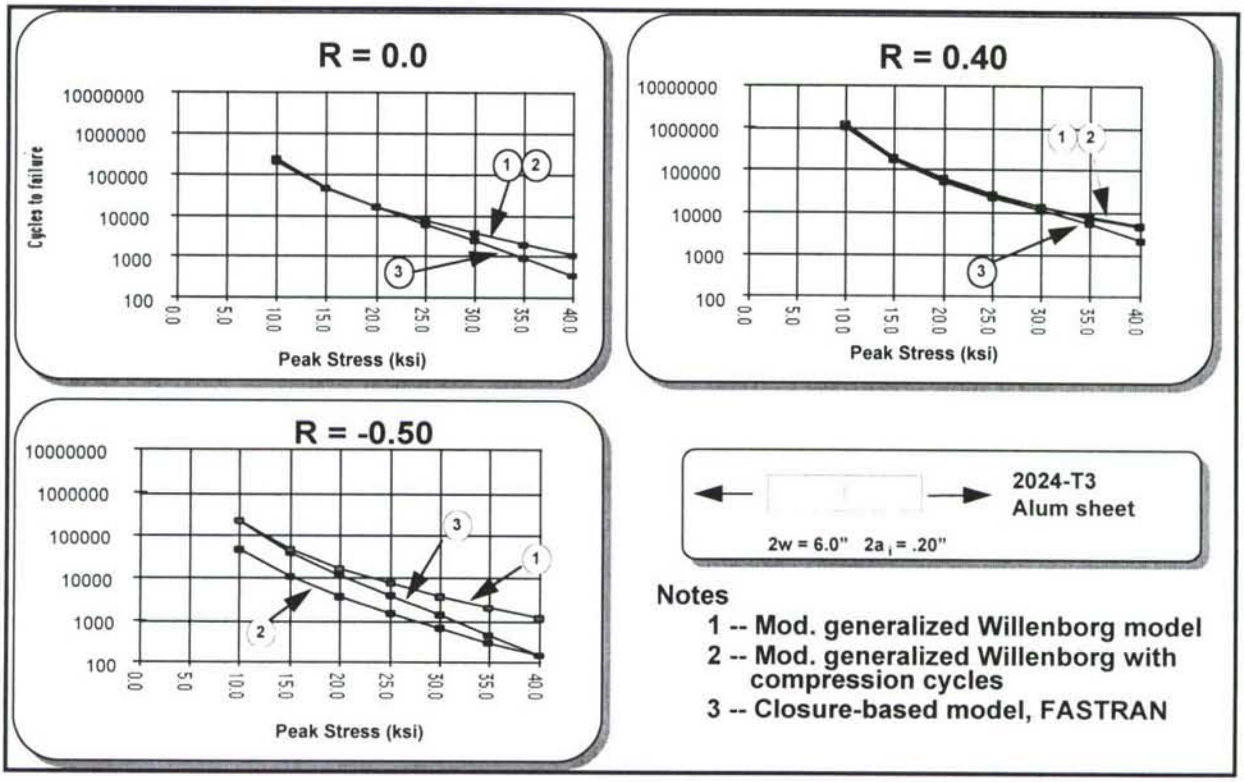


Figure 3. FASTRAN Comparison - Constant Amplitude Loading

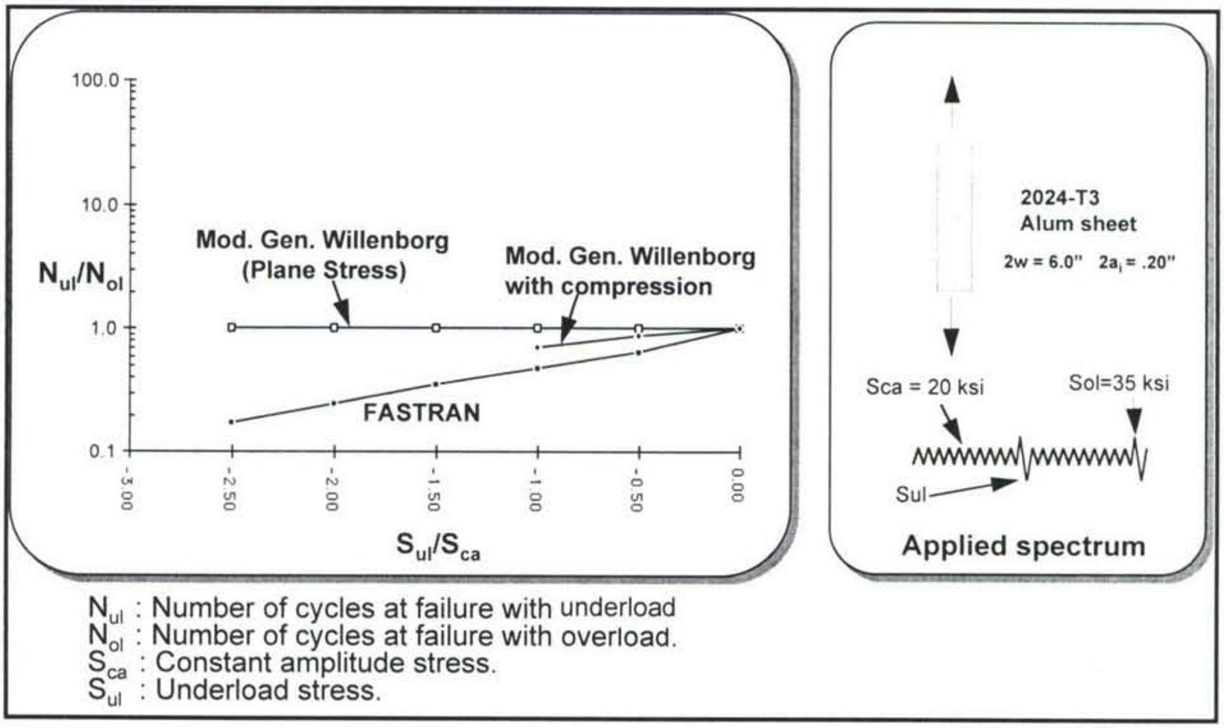


Figure 4. FASTRAN Comparison - Effects of Overload

Regulations for Continued Airworthiness - Damage Tolerance in its Widest Sense

Dayton Curtis
Federal Aviation Administration
Northwest Mountain Directorate

INTRODUCTION

In 1944 a professor from Columbia University wrote a book entitled "Teacher in America" which described some problems with our educational system. It was very successful, becoming required reading in many university classes, and earning its author high praise. In a new introduction written for my 1959 edition of that same book, the author said that he felt very honored by the enthusiastic reception his book had received and the high level of interest it continued to generate. At the same time he was dismayed that there had been so little improvement in the field of teaching in the 15 years since the book's introduction. It seemed just as current and pertinent in 1959 as it was in 1944.

In some respects I feel like that college professor. I'm honored to be asked to speak again on the Aging Aircraft Program, although it certainly isn't just my program. At the same time it is disappointing that over 7 years have passed since this program began, and we are just now beginning to have a real influence on the aging fleet. The first of the modification ADs became fully effective on the fleet only about one year ago, and the first corrosion ADs have produced only a few repeat inspections, which would really measure their effectiveness. Other aspects of the regulatory programs were completed later than those two or are not even done. So the full effect of the aging aircraft program has yet to be felt.

On the other hand, the operators, and those of us who support the operators, have responded to the aging airplane problem admirably. There has not been an aircraft accident or incident in these past 7 years that could be attributed to the age of the airplane. As a direct result of this, we recently got a very good report card from the media on our efforts. The news media, of course, both reflect and guide public opinion.

A GOOD REPORT CARD

Newsweek magazine for April 24, 1995, had this to say:

"Metal fatigue, or the cracking that results from repeated stress, is generally not an issue - even with older planes. FAA regulations dictate that planes must be overhauled every three to four years and retrofitted with the safety features of new airplanes. So checking a plane's vintage may not tell you much about its airworthiness."

Despite the glaring errors in this assessment, it is probably an accurate expression of the current media attitude, public opinion, and congressional concern. More recently, the June 26, 1995, issue of U.S. News and World Report attacked the FAA vigorously on a host of safety issues, but was silent on aging airplanes. The good news is that these public report cards seem to recognize our achievements in handling the aging aircraft problem. We - the operators, manufacturers, airworthiness authorities, and others - have succeeded in quelling public hysteria over aging airplanes. The accident/incident record has spoken for us.

The bad news is that the potential problem with aging airplanes is not yet completely solved or accounted for, and this more complacent attitude on the part of the media, the public, and congress is pulling away the support we need to get the task finished. Finishing the task is the main theme of this talk, so I would like to review quickly both the process and progress so far.

PROCESS AND PROGRESS

To address the aging airplane problem, an advisory committee approach was used. The group consisted of operators, manufacturers, airworthiness authorities, the National Aeronautics and Space Administration, Airline Pilots Association, International Association of Machinists, Association of Flight Attendants, etc. Although the internal arrangement has changed over the years, the operators, manufacturers, and airworthiness authorities remain at the core of the advisory group, and all of the interested organizations still participate in, or influence, the aging aircraft program.

The objective of the advisory group, as I understand it, was to recommend actions that would "maintain the structural integrity of each airplane in the fleet at the level assumed to exist at the time that airplane was first approved, for as long as the airplane remains in service." The objective, then, was not to raise the level of safety, but where the originally assumed safety level was not being achieved in service, additional actions would be proposed to restore that level. This process had actually already begun for most of the aging airplane models with the introduction of Supplemental Structural Inspection Programs, mandated by airworthiness directives.

The advisory group initially proposed these five, by now very familiar, actions to achieve this objective. All were to be mandated by airworthiness directive except the maintenance program guidelines, which would be voluntary. Later in the program a sixth item was added on widespread fatigue damage.

I would like to interrupt the discussion here for a brief side comment. This statement appeared in the August 8, 1994, issue of Aviation Week. **"Airlines . . . fault the agency for abusing the use of airworthiness directives as one means of implementing its aging aircraft program."** I have heard similar statements from some newer participants in recent aging aircraft meetings and would like to take this opportunity to correct the record.

As should be apparent from the preceding items, the statement in Aviation Week is historically incorrect on two counts. First, it is not the FAA's aging aircraft program. It was, and is, an advisory group program. Second, it was not the FAA, but the advisory group, that recommended AD action on all but one of the original tasks. I know that is hard to believe from today's perspective, but there was strong operator support for AD action initially. The first arguments I heard against using ADs came from within the FAA, and they caused a strong negative reaction when first presented to the advisory group.

We all know that times have changed, and that operators no longer favor ADs as a means of implementing aging aircraft actions. The FAA had previously changed, and now favors the use

of operational rules to implement these actions, although not without complaints from some other quarters. Those complaints will be mentioned again later.

Continuing now, the aging aircraft actions were initially proposed to affect only the eleven oldest large jet transports then in service. This fleet has not changed.

Considerable progress has been made in carrying out these planned tasks. All eleven of the assigned airplane models are now covered by modification ADs. All are now covered by Corrosion ADs and by new or updated Supplemental Structural Inspection Program (SSIP) ADs. The voluntary Structural Maintenance Program Guidelines have been available for some time. As just mentioned, the FAA is moving away from the use of ADs, so the Repair Assessment task is being recommended as a change to the operating rules. The final working group draft on Repairs is now in the FAA for detailed legal review before being formally recommended by ARAC. The widespread fatigue damage task has been completed as a recommended amendment to Advisory Circular AC 91-56, and is now in the FAA for final action.

Although these tasks has taken longer than any of us expected, they now seem to be drawing to a close. The progress I have just described, when finally published and fully effective, will essentially complete what the advisory group set out to accomplish. When that happens, all of us who participated in this process can be justifiably proud (and relieved). Balanced against this good feeling is the nagging doubt that the task really will not be complete as it is described above. I would like to look at the whole picture one more time and state briefly what I feel may be missing elements in the overall task.

A DAMAGE-TOLERANCE APPROACH

I would like to start with the FAA's attempt to assure structural integrity, other than by simply being very conservative. The conservative approach did work well, as the continuing service of 50-year-old Douglas DC-3's indicates. But even the venerable DC-3 had some in-flight structural failures, and the FAA adopted a fail-safe/safe-life approach to counter the weaknesses of simple conservatism. It then turned out that the fail-safe approach had its own weaknesses and the damage-tolerance concept was adopted. To my knowledge, no one has come up with a

better way to assure the structural integrity of commercial airplanes than damage-tolerance, so I'd like to review what that is, and how it is being - and might be - applied to the fleet.

First a definition. There are many definitions of damage-tolerance floating around. A good one comes from a paper by Ulf Goranson which he presented at the 17th Symposium of the International Committee on Aeronautical Fatigue in Stockholm, Sweden, in June 1993. That definition reads, "Ability of structure to sustain anticipated loads in the presence of fatigue, corrosion, or accidental damage until such damage is detected through inspections or malfunctions and repaired."

I'll confess I'm a little nervous about the "..until such damage is detected through ...malfunctions.." part. That has not always worked as expected. But there are places in a typical airframe where the concept is still valid. What makes this definition preferable to me is the fact that it clearly indicates the need for inspections. Damage-tolerance is not a complete concept without these inspections.

It is possible, of course, to design a structure that would meet all of the damage tolerance requirements when inspected in accordance with the most relaxed maintenance program likely to be approved for the least conscientious operator of that airplane no matter how long it remains in service. That structure would be truly damage tolerant - no special inspections required. But it is difficult to imagine an airplane that would be competitive in today's market that has been designed so conservatively. By this definition then, there would be very little damage-tolerant *structure* in commercial aviation. Rather, a particular design together with an approved maintenance program and mandated special inspections could be said to be damage tolerant.

In this regard we heard Tony McBride of UPS say yesterday that ADs should not be used for routine maintenance. Most of us in the FAA agree with that, but we also note that some actions, like these damage-tolerance based inspections, are not routine maintenance. That is, the operator cannot change the inspections, thresholds, or intervals based on his own service experience. Damage-tolerance doesn't work that way. This issue may need further discussion if we are to fully understand each others position.

An airplane is also not damage tolerant if the assumptions that the inspection interval calculations are based on are not met in service. One of these is the probability of damage detection. The inspection intervals are chosen to give a reasonable chance of detecting fatigue (or other) damage before it becomes a hazard to flight. If the inspections are not as reliable as was assumed in setting those intervals, for any reason, then the airplane will not be truly damage tolerant.

In the same way, if the structure is significantly corroded, then the material's assumed load carrying ability and crack growth rate characteristics would be changed, and the calculation of inspection thresholds and intervals would be incorrect and unconservative.

Similarly, if there is bonded structure, and some disbonding has occurred, the calculated or tested fatigue data will be wrong and so will the damage tolerance calculations; *unless* the disbonding is anticipated and has been specifically accounted for in tests and in the damage-tolerance calculations. This same precaution applies to any other unique structural feature upon which the damage-tolerance calculations depend.

The airplane would also not be damage tolerant if only a part of the critical structure is covered. All structure upon which the safety of passengers and crew depend must be covered, whether it is original, modified, repaired, altered, or replaced (i.e., cannibalized from another old airplane). Each of these nonoriginal conditions brings with it its own set of problems. Some of these changes to the structure originate with the original manufacturer or OEM, some with a Supplemental Type Certificate (STC) holder, some are approved by independent Designated Engineering Representative (DERs), etc. Each must be accounted for.

Finally, the airplane cannot be considered damage tolerant if the residual strength of any critical structure is degraded by the presence of widespread fatigue damage (WFD). Widespread fatigue damage must be predicted, verified, and removed from all structure affected by § 25.571.

I'll end my list at this point with seven items. Some of you may wish to add to, combine items in, or subtract from this list or scrap it entirely. But it is a starting point for further discussion.

To measure our progress in meeting these conditions so far, let's look at how these seven items fit with the tasks we've already completed on the eleven models. The first two requirements are met by our existing Supplemental Structural Inspection Document (SSID) ADs. The probability of detection issue is addressed by the Modification ADs and the corrosion issue by the Corrosion ADs.

I would like to make another side comment here. The product of the working group for the corrosion task is often referred to as the Corrosion Prevention and Control Program. I have heard people say that it should really be called just the Corrosion Control Program since no one can really **prevent** corrosion. I strongly disagree. I've heard similar comments about the FAA Administrator's goal of Zero Accidents. "You can never completely prevent accidents", they say. Well maybe not, but you sure aren't going to set peoples expectations very high if your goal is to **have** accidents, however few. The goal must always be Zero Accidents.

In the same way, the results of any corrosion control program are determined partly by the expectations of the people doing the job, and their expectation should be set as high as possible. Don't just remove corrosion, prevent it. Clear those drain holes. Dry the insulation blankets. Apply corrosion inhibitor wherever appropriate!

Recent comments I've heard from industry indicates that there are now some inhibitors that almost really do prevent corrosion in certain applications. That is where the real gain is to be made, both for safety and for airline economics. Don't just clean up the old corrosion, prevent the future corrosion. Just the attempt will pay off in many ways!

Going on down the list, there is no aging airplane action for disbonding since it is a design specific condition. There may be references to it in the material on corrosion, of course, and for this and other model specific problem areas there may be individual ADs.

The need to include structure that has been changed after manufacture is being addressed by the Aviation Research Advisory Committee's (ARAC) proposed Repair Assessment operating rule.

This task includes an agreement with the OEM's to update the FAA approved Structural Repair Manuals and mandated Service Bulletin modifications to damage-tolerance status.

The proposed repair assessment rule, however, is limited to just the external fuselage pressure shell. This was done to speed up the process and focus our resources on the area of greatest need, much as the overall task was limited to just eleven models. It is expected that repairs to the remainder of the airplane will be considered in the future.

Finally, ARAC has recommended a new appendix to AC 91-56 to call for the prediction, verification, and removal of widespread fatigue damage. When WFD is identified, its removal may be further mandated by AD.

So basically all seven of the damage-tolerance concerns listed above have been covered by the aging aircraft program and the assigned ARAC tasks, and the whole exercise of breaking down the damage-tolerance task and listing the seven items above was a big waste of time. Well, maybe not. Before deciding on that let's look at the whole picture one more time.

A DAMAGE-TOLERANT FLEET

To start, let me restate the objective. "Maintain the structural integrity of each airplane in the fleet at the level assumed to exist at the time that airplane was first approved, for as long as the airplane remains in service". This is the same objective you've seen before. One item that has clearly not been accounted for is the total fleet. The advisory group limited their initial actions to the eleven oldest models of large jet transports in order to focus our resources on the airplanes most in need of attention. That was a wise and prudent decision.

The time has come, however, when we must move on to consider the remaining fleet. This will not be an easy task, since the fleet contains airplanes with many different certification bases.

The definition given earlier describes the conditions under which a piece of structure could be found to be damage tolerant. For a complete airplane to be considered damage tolerant per §25.571, all seven of the conditions listed above must be adequately addressed. The air transportation fleet could be considered damage tolerant when each airplane in that fleet meets

all seven of these conditions. It should be obvious that if we really wanted damage-tolerance principles to apply to the entire fleet used in air transportation, aging or not, we have some work left to do.

Nevertheless, looking at this total fleet from the point of view of compliance with the damage-tolerance philosophy, I'll roll out those seven items again.

First, a damage-tolerance evaluation (asked for only in AC 91-56 for the eleven models) is now required by § 25.571 for post Amdt. 45 airplanes. The associated inspections are now specifically required for post Amdt. 54 airplanes by FAR § 25.1529 "Instructions for Continued Airworthiness". To make these requirements more generally applicable, the FAA is now considering a proposed new operational rule to mandate these supplemental structural inspections.

The probability of detection issue was to be covered by an advisory circular to make sure that future aging airplane service bulletins modifications would be mandated only in accordance with the agreed criteria. Despite the trouble that some structures task groups have experienced in this area, that little AC has had a difficult time getting the recognition it deserves within FAA, and it is shown here in lighter type to indicate its problematic status.

For corrosion, however, there is an active rulemaking effort underway to add a requirement for a corrosion prevention and control program to the operating rules. Although that task is being handled within FAA, rather than through ARAC, an accompanying advisory circular on corrosion is now being reviewed by an industry group.

Model specific structural problems will continue to be handled by model specific service bulletins and ADs.

The issue of including all critical structure on the total fleet is much more difficult. For repairs and service bulletin modifications, the six manufacturers in the current aging airplane program have generally agreed to provide damage-tolerance based inspection information where needed. For the rest of the fleet, there is no such agreement, however, the later FAR 25 designs do have

such a requirement implicit in their certification basis, and it is expected that the manufacturers will comply.

The issue of changes made by parties other than the manufacturer still needs work. The certification basis of later designs dictates a damage-tolerance assessment of changes to any critical structure, but getting consistency in this area has not been easy. Independent DERs must also abide by the requirements of the type certification basis, but guidance and consistency problems remain.

I have tried very hard to get a workshop going within FAA to assure consistency between and within ACOs at least, but have failed to get the needed resources in this time of dwindling budgets and competing safety concerns. I'm still trying.

To address the replacement parts issue, an AC on cannibalization and associated record keeping has been drafted.

On the subject of widespread fatigue damage, the new appendix to AC 91-56 recommended by ARAC will serve to task the manufacturers of those airplanes specifically identified in the proposed new appendix. Although it is clearly not mandatory, these manufacturers have agreed to comply. For other existing airplanes, the subject is not yet addressed.

For future designs, the FAA is proposing a new requirement in § 25.571 for full scale fatigue testing, one objective of which is to assure freedom from WFD within that model's first design service goal. For operation beyond that point, there is no proposal at this time.

FINISHING THE TASK

If you would now indulge me one last look at the objective, this is what I think we set out to accomplish. To maintain the structural integrity of each airplane in the fleet for as long as the airplane remains in service. It is what I think congress and the public expect from us.

To finish that task the following is what I think still needs to be done. I suggest taking the previous list, or someone else's similar list, as a starting point and working together in an

advisory group setting, decide on what specifically needs to be done, or can reasonably be done, to assure the safety of the entire fleet, reviewing the costs and benefits of each proposed way of accomplishing the work, and recommending action where appropriate. Yesterday we heard Ron Wickens of Fed Ex, and the former chairman of ARAC's Airworthiness Assurance Working Group, say that ARAC is not working all that well. But ARAC is not the only possible advisory committee approach. We need to work on that issue as well.

I know that few in the air transportation business today relish the thought of considering more meetings, much less more regulation, guidance material, or advice. In defense of continuing this work in the face of such attitudes, where they exist, I would like to restate the FAA's role as I understand it.

I'm sure you are all aware of FAA's so called "dual mandate" in promoting and regulating civil aviation. The way we view this in aircraft certification is that we can best promote aviation by making it safe. We can then meet both directives by taking such steps as are necessary to assure a safe air transportation system.

In the FAA's aircraft certification offices, we view our own charter and our responsibility to the public as a mandate to assure a **safe** air transportation system. We have always considered safety our first responsibility, and always will. However, we cannot forget the rest of the sentence in that charter. We must also make sure there is an available **air transportation system**. While safety is our first concern, the air transportation system must also be as available and as affordable as possible to serve the public. To meet this part of our charter, we have to find ways to achieve our safety goal that are both cost effective, and that do not unnecessarily hobble the industry in the management of its own affairs. This is not an easy balance to strike.

In asking for further meetings on continued airworthiness, and a consideration of the larger fleet, I also ask that we all keep in mind the above charter and work to achieve our goal with full consideration of the necessity to balance the safety equation as stated above.

Continuing on, the task will also remain incomplete until we harmonize the results with JAA and others. Presently, those tasks imposed by AD are easily adopted by other airworthiness

authorities. The tasks we impose by changes to the operating rules are not immediately adoptable, and when, and if, that eventually becomes possible, some harmonization work will need to be done.

Finally, the task will not be done if it applies to only a few countries in the world. A real effort must be made to find some way of providing the benefits of our continuing airworthiness work in a manner that is acceptable to, and adoptable by, all ICAO member countries. At present there are no plans to create the regulatory environment needed to adopt an operating regulation by most countries, and it is from these countries that I have heard the most vigorous complaints about our plans to use operating rule changes in place of ADs. It may be difficult to work an ICAO task within an ARAC, or similar setting, but there are real problems here waiting to be solved.

So, to finish the task I propose these three items. None of them will be easy. Why, you may ask, should we tackle these difficult problems now? Why not wait and see what future service experience indicates is really important before devoting any more time and effort to this? Well, the wait and see approach is also now being called the "tombstone technology" approach. Besides there are some benefits to wrapping this business up, if it can be done correctly.

BENEFITS

The primary benefit from our standpoint, of course, is improved safety. But there are other benefits as well. First, addressing the task in this way will provide a cleaner environment for the regulation of continued airworthiness. Fewer bandages (ADs) should be needed to patch the system, compared to simply allowing problems to develop.

It will also provide a leveler regulatory playing field for competing organizations. Especially so if real harmonization is achieved.

Economics is not my field, and I know that operating costs are driven by many factors. Perhaps this is relatively minor one, but it would seem that improved safety, fewer ADs, and a level playing field would help the bottom line. In any case, the benefit of some of the aging aircraft

tasks, like the one on corrosion, can be shown to reduce down time and improve dispatch reliability.

Finally, there is a tangible measure of political insurance in completing this task. Any person who has had to stand before a congressional committee, a judge, or an NTSB hearing, can tell you that having completed a task like this one gives them an enormous advantage in defending their actions, or their organization. If full international agreement can be reached via ICAO, it will be even better.

An important aspect of continuing to work in this way is for the FAA to acquire the resources to respond to ARAC or other recommendations in a timely manner. At present, the workload from all sides has quite overwhelmed our limited capacity to provide a meaningful response in the time frame expected. In the midst of government-wide streamlining, acquiring the needed resources has proven to be extremely difficult. There is hope, however, and by the time we are ready to make future recommendations this situation should have improved.

CONCLUSION

The suggestion you've just heard here about finishing the task is not new. The proposal to work the issues via an advisory committee is not new. The list of issues remaining to be addressed is not original. In fact, this is only one of a series of messages being sent by various people and organizations to keep our collective eye on the objective and to keep working at it until we're done.

I know that continuing what has become a grinding chore in some instances is not very appealing, but we must make the effort. It is understood that actions, or inaction, proposed by some participants may not be balanced by equal or better benefits. The best way to make sure that only the best proposals are adopted is active participation. It is extremely important that we sit down together and look at each of these issues.

I cannot predict the future, but it seems inevitable that sooner or later some of us will be called to account for our actions on aging airplanes and continued airworthiness. When that happens the

best hope for the future of the air transportation industry is that we can respond that we have looked at everything and we have done, and are doing, our level best to address in some way every single safety related aspect of airplane structural integrity.

To put our activity and our achievements in perspective, I'd like to refer again to the book, "Teacher in America" with which I started this talk. In the introduction, written fifteen years after the book's original publication, the author referred to what he called the book's "indecent longevity". Well that book is still in print today, 50 years later, in both hard cover and soft, and it is still pertinent. The author no longer complains about the book's longevity; the book, and the problems it describes, having outlived him. Many of our cherished democratic institutions do not change very fast.

By comparison, what we have **already** done in our area of expertise is a testament to effective group action. The original Aging Aircraft Task Force broke new ground, set new precedents, and exceeded all of our expectations in many respects. What we **will** do, in finishing this task, will also stand as an example for future group activities on safety issues. We now have the choice to make that example anything we wish.

Regulations Affecting Air Carrier Structural Inspection Programs

David Lotterer
Air Transport Association

You heard the comments of Tony McBride earlier on the Airworthiness Directive (AD) process and its impact on airline maintenance. I want to share with you what some of the industry working groups are doing to improve the AD process and highlight some areas that from an airline point of view, need more work.

IMPROVING THE AD PROCESS

Let me start by reviewing what the industry and the Federal Aviation Administration (FAA) are doing to improve the AD process. You heard Tony McBride speak of the "lead airline" process. The idea here is for the lead airline to work closely with the manufacturer to improve the quality of the service bulletin referenced in the AD. If prototype development is needed to verify the accomplishment instructions before the service bulletin is issued, then that's what the lead airline will do. Rewriting the service bulletin and developing data to provide complete repair instructions and reviewing variations in configurations can be done better if the airlines and manufacturer work closely together well before the AD is issued. All airline comments are important to a manufacturer. But when you make one operator responsible for the task, the quality of the airline input goes up considerably. I remember last year that for a component inspection program, the lead airline had inspected over 260 components well before the Notice of Proposed Rulemaking (NPRM) was issued. This process works well when a new service bulletin is just being developed. It needs improvement when an old service bulletin is resurrected to fit an AD. We have found that the FAA and airframe and engine manufacturers have been very supportive of the lead airline process.

Another positive idea is to make an AD compatible with the service bulletin it references, both in accomplishment instructions and in compliance periods. It sounds simple but it really takes a good deal of effort by the airlines, the manufacturer, and the FAA staff. Operators should not have to work to two separate documents to do the same task. Since the FAA-ACO must approve the service bulletin before it is referenced in an AD, it should be the exception rather than the

rule that an AD should have additional provisions. An engine fan blade inspection AD was recently published that stated simply to accomplish in accordance with the intervals and procedures provided in the referenced service bulletin. That was it! The rest of the AD was boilerplate. Several conference calls were necessary and we worked with FAA staff who were willing to try a new approach but things can happen if people are willing to improve the process.

AIRWORTHINESS DIRECTIVES- REPAIR REQUIREMENTS

Another cooperative activity currently underway between the FAA and industry is the ARAC/Alternate Means of Compliance (AMOC) Working Group. This group has been tasked to develop recommendations for improving the AMOC process. Last year nearly 1,000 AMOC's request were submitted to the various FAA Aircraft Certification Offices (ACOs) and the majority were for approving structural repairs required as a result of AD inspection findings. Most often an operator seeks original equipment manufacturer (OEM) assistance in developing the substantiating data and then must request FAA ACO approval before proceeding with the repair. The preliminary conclusions reached by this working group is that since the OEM have the type certificate data, why not delegate to the OEM Designated Engineering Representative (DERs) the authority to approve the repair? The DERs would follow up with reporting the repair to the FAA ACO but the operators could proceed with the repair once concurrence by the OEM DER is obtained. The FAA staff on this working group feel comfortable with delegation of permanent repairs but are as yet undecided on to handle time-limited or interim repairs. Certainly a repair that restores the aircraft to its type certificated basis should be delegated to the OEM DER process but what about time-limited or interim repairs. The AD itself can have a provision that provides operators the opportunity to "accomplish repairs in a manner approved by the FAA" would negate the need to submit an AMOC request for time-limited or interim repairs. This is not delegation but a provision of the AD. This provision was common in ADs in previous years and ATA members believe the practice should be resurrected. The working group as yet has not agreed to a recommendation on handling time limited or interim repairs. The working group is committed however to meaningful recommendations to improve the AMOC process.

What needs further work?

If we continue to emphasize the importance of issuing ADs to address airworthiness issues, can we conclude that an operator's maintenance program requirements are limited to general inspection programs and that anything critical to airworthiness will be made into an AD?

If from a business perspective, the FAA-ACOs and the AD process will take care of your airworthiness issues, why do you need all those structural engineers at the airlines?

AIRWORTHINESS DIRECTIVES - A RISK MANAGED APPROACH

Under FAR 121, an operator is responsible for the airworthiness of its fleet. Operator's achieve this through their FAA approved maintenance programs. There's nothing written anywhere that says operators achieve this just by doing ADs. Clearly an operator's maintenance program outside the AD process remains an integral part of achieving airworthiness. So who decides what part of airworthiness is covered by ADs and what part is covered by the maintenance program? Right now the FAA certification offices decide. Is their determination to adopt AD mandated inspections proactive or reactive. Is it objective or subjective?

The JAA recently issued a draft Part JAR 39 which defines what is "unsafe". FAR Part 39, the rules that provide for ADs, don't provide this. You need to define what is unsafe first before you can develop a risk assessment process to support AD rulemaking. Is airworthiness simply the process of restoring an aircraft to its original type certificated basis? Or is it more?

FAA New England recently proposed an Advisory Circular on Airworthiness Assessment of Engine, Propellers, and APUs. Its purpose was to use risk assessment tools for both the engine manufacturer and the FAA to use in identifying airworthiness concerns, prioritizing such concerns, and resolving such issues. A risk assessment program that looks at structural airframe events would be a good first step toward a complete risk assessment management approach in dealing with airworthiness issues. ATA members and airframe manufacturing are in the process of proposing that what was done on the engine side of business should be done on the airframe side of business but we need buy-in by the FAA-Seattle Certification Office before it can

proceed. ATA members believe that a standardized process of risk assessment will be a valuable tool for the FAA-Seattle ACO, and for that matter the entire FAA, in determining what inspections are AD subject matter and what inspections are maintenance program adjustments.

Assuming we can all agree to objective criteria that establishes what is unsafe, what about the airworthiness concerns that fall into the area shaded "grey"? "Grey" is below the requirements of an AD but above that which is considered adequate in an operator's maintenance program. Are the ACOs and the FSDOs communicating sufficiently to respond to these shades of grey? This is clearly within the purview of an operator's maintenance program. The FAA, as well as both the certification offices and the FSDOs, need a coordinated program in place to determine how to address all airworthiness issues. Cranking out more ADs is not a long term solution to maintaining airworthiness in our fleet.

We need to limit Part 39 rulemaking for its intended purpose and to restore an operator's maintenance program to its full potential, preferably using existing Part 121 rulemaking.

Again, there is again much discussion between the FAA and industry on reliability program adjustments particularly as they relate to structural inspections. Are the standards for making program adjustments adequate? I understand that an ARAC group recently provided the FAA an update on the Advisory Circular for Reliability Programs and the FAA is having second thoughts on its issuance. If there are still legitimate concerns, then there should be a cooperative effort between the FAA and industry to resolve them.

Another area of controversy is the authority of the FAA to make program adjustments. The FAA is developing a proposed Part 121 rule to mandate that an FAA approved Corrosion Prevention & Control Programs (CPCP) be incorporated into an operator's maintenance program for each fleet type. ADs with not be issued for airplanes certificated to damage tolerant standards. What about adjustments to such programs as the fleet ages? I understand that a basic ETOPS maintenance program document is being developed and will be incorporated by the ETOPS operators. Once that's done, subsequent revisions to the program will be mandated by ADs. Is that the approach that will be taken for corrosion programs of damage tolerant airplanes? This is

one area of FAA policy that needs to be straightened out. When MTF recommendations were first issued, ATA members supported the use of the AD process to mandate these maintenance program inspections since we were responding to immediate aging aircraft concerns. Now that 7 years have passed, is the issuance of more maintenance related ADs still the only choice?

PROPOSED AMENDMENT TO FAR PART 25.571 DAMAGE TOLERANT STANDARDS

Some brief comments on damage tolerant standards. In 1993 the FAA proposed a rule change to the damage tolerant standards that read "Widespread multiple-site damage will not occur within the design lifetime of the airplane." ATA members expressed concern over the FAA's future interpretation of these words should this rule be adopted without change. Does this mean that this is an "absolute" design requirement or is the elimination of widespread multiple-site damage a "goal"? We are hopeful the FAA will choose its words wisely. An airplane's structure needs to be light enough to carry a payload.

ATA members also expressed concern that the proposed companion AC to this proposed rule change would establish SSIP inspection thresholds based upon a rogue flaw analysis. The MTF Structural Fatigue and Evaluation Task Group considered using the rogue flaw method of analysis but abandoned that approach as too conservative and recommended the classical fatigue analysis methods. There are several ways to crack a nut. ATA members request that the FAA adopt a rule that supports the recommendations of the Maintenance Working Group (MWG) Task Group. A rouge flaw analysis is fine for incorporation into a OEM quality control program at the time the aircraft is being built but it shouldn't dictate the Supplemental Structural Inspection Document (SSID) inspection intervals for the operators.

SUMMARY

In summary, ATA members appreciate FAA's recent efforts to improve the AD process. In seeking further improvements within the regulatory process, we would like to see greater acceptance within the FAA of a more objective approach toward determining whether ADs should be issued and what is an acceptable compliance period. Acceptance of risk assessment methodology will help define the limits of an AD. Once that is done then we need to put in place

a process that picks up other issues of airworthiness. Perhaps we should look at how effective Flight Standards are in their oversight responsibilities of an operators maintenance program. We may need to break some of the walls down between the FAA-ACO and Flight Standards. Perhaps even some rule changes within Part 121 may be required if Flight Standards views their ability to implement legitimate program adjustment as ineffectual. If maintenance program requirements are broken, then let's fix it by constructively working together with a solution everyone can buy into.

INSPECTION PROGRAMS FOR DAMAGE TOLERANCE—MEETING THE REGULATORY CHALLENGE

Lance A. Hidano and Ulf G. Goranson
Boeing Commercial Airplane Group
Seattle, Washington

ABSTRACT

Established maintenance practices have demonstrated good safety records for today's in-service airplanes. However, as these airplanes exceed their design service objectives, many in the industry have wondered if the fail-safe design principles used in the 1950s and 1960s are adequate. In recent years, regulatory authorities have raised a number of specific aging airplane concerns, which have been, or are currently being, addressed by the industry. This paper summarizes the successful efforts of the past and looks ahead at two damage tolerance inspection programs that will soon be in place for the aging fleet.

INTRODUCTION

The design of safe and competitive jet transport structure is an evolutionary process that takes advantage of lessons learned over the years. Regulatory requirements that establish the minimum design standards have also evolved over time, and, as a result, older in-service airplanes have usually been certified to less stringent rules. An example of this is the requirement for damage tolerant design and maintenance principles. Airplane models certified before 1978 are not required to satisfy the current damage tolerance requirements of Federal Aviation Regulation (FAR) 25.571, Amendment 25-45. This is a concern to some who feel these aging airplanes require additional action to remain safe.

The airline industry has always been committed to maintaining safety of the fleet and has an excellent safety record. This has been achieved through diligent attention to detail design, manufacturing, maintenance, and inspection procedures by the manufacturers, the operators, and the airworthiness authorities. When recently challenged to address the safety of aging airplanes, the industry responded by forming model-specific task groups to develop the following programs:

- Service bulletin modification.
- Corrosion prevention and control.
- Basic maintenance program review.
- Supplemental structural inspection.
- Repair assessment.
- Widespread fatigue damage assessment.

This paper summarizes the successful efforts of the past and looks at future damage tolerance inspection programs currently in work. All manufacturers of commercial jet aircraft are currently developing similar programs to address the concerns of the regulatory agencies. A uniform approach is an objective of the industry; however, it is recognized that in such a complex field, variations are to be expected. This paper therefore provides an overview of the programs implemented, or currently under development, by one manufacturer, Boeing.

Evolution of Design Principles

Static Strength Design

Structural design criteria has evolved since the infancy of aviation to achieve structural strength in the absence of accidental, corrosion, and fatigue damage. Design limit loads for maneuvers, gust, and ground loading conditions are based on millions of commercial airplane flights. Analysis tools have also evolved over time based on lessons learned. As a result, it is exceptionally rare for airframes not to attain design ultimate loads in full-scale verification tests.

Safe-Life Design

In the early 1950s, it became clear that static strength criteria had to be supplemented by estimated replacement times for some critical structural elements. This resulted from the use of high-strength aluminum alloys without corresponding increase in fatigue strength. In general, the safe-life design philosophy for continued airworthiness was successful. This was primarily due to rapid technology developments rendering airplanes obsolete before they seriously challenged the established life limits. Today, safe-life design principles are typically limited to ground loaded structures, such as high-strength steel landing gear components.

Fail-Safe Design

Commercial jet transport structures have been designed and certified according to a fail-safe philosophy since the mid 1950s. Thus, airframes with significant structural damage have the ability to sustain the maximum anticipated loads. Service experience has shown that this design philosophy has generally allowed sufficient opportunities for timely detection of structural damage, as thousands of cases of fatigue and other types of damage have been detected and repaired on in-service airplanes.

Cracking patterns experienced in service have frequently been different than assumed during the fail-safe analysis. This is particularly true when fatigue is the primary source of damage. Structure adjacent to the primary fatigue crack may itself contain a number of cracks. This multiple-site damage can significantly reduce the residual strength and crack-arresting ability of the structure, and therefore the fail-safe design philosophy may not always be conservative enough.

Damage Tolerant Design

Combined industry and airworthiness authority activities in the late 1970s promulgated necessary changes of the regulatory requirements to reflect the deficiency of the fail-safe design philosophy. In addition to a high residual strength or fail-safe capability, damage growth and inspection requirements considering damage at multiple sites was incorporated in FAR/Advisory Circular (AC) 25.571, Amendment 25-45. Certification of commercial jet transports currently mandates damage tolerant designs in all instances where it can be used without unreasonable penalty.

The vast majority of commercial jet transports in service today were certified fail-safe or damage tolerant. Boeing fail-safe airplanes, such as the 727, were certified to different regulations but have detailed structural components that are nearly identical to comparable ones on airplanes certified damage tolerant. Therefore, with proper maintenance, these fail-safe airplanes can satisfy the intent of the damage tolerance regulations.

Primary airframe components are designed to carry ultimate design loads, which typically exceed envelope limit load conditions by 50%. As previously discussed, the analysis methods and limit load conditions are based on the lessons learned from millions of commercial airplane flights; hence, there is high confidence that the undamaged structure is safe. However, as an airplane accumulates service time, damage may occur that reduces the static strength capability, as shown in figure 1. Structure is damage tolerant if the damage that may occur will be discovered and repaired before the residual strength falls below the required level. Consequently, to be damage tolerant, a structural inspection program must be in place to ensure the damage will be detected. The severity of this inspection program is dependent on the duration of the detection period, which is defined as the time to grow a crack from its detectable length to its allowable or critical length.

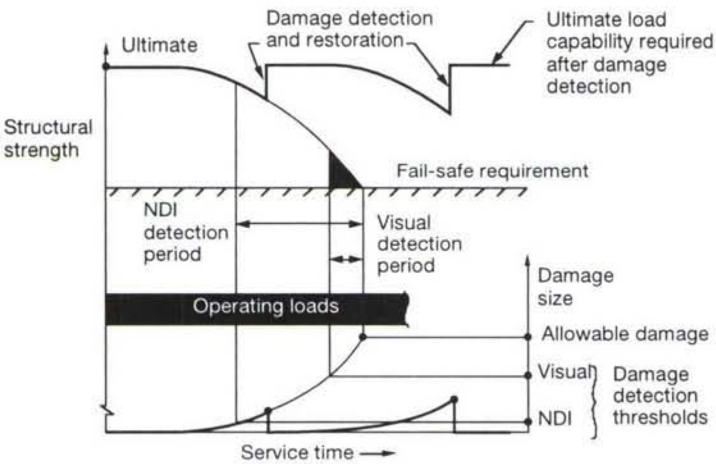


Figure 1. Strength Requirements for Damage Tolerant Structure

Damage tolerance thus comprises three distinct elements of equal importance to achieve the desired level of safety. A brief summary of these elements follows. (Ref. 1 discusses these elements in depth.)

Residual Strength

A residual strength analysis is used to determine the maximum allowable or critical damage that a structure can sustain at fail-safe load. Structure with good damage tolerance has high residual strength, which results in large critical crack lengths and long damage detection periods.

Crack Growth

The rate of damage propagation is a function of material properties, structural configuration, environment, crack length of the primary and secondary cracks, and operating stresses. A damage tolerance assessment requires crack growth data from the detection threshold to the critical damage. Good damage tolerant structure has slow crack growth, which results in a long damage detection period.

Damage Detection

The goal of a damage tolerance inspection program is to find the damage before it reaches critical length. To achieve this objective, a sequence of inspections, with methods and frequencies specified, is selected for a fleet of airplanes.

REGULATORY CHALLENGE

In 1978, the Federal Aviation Administration (FAA) revised FAR 25.571, "Damage Tolerance and Fatigue Evaluation of Structure." This revision requires an evaluation to ensure that should serious fatigue, corrosion, or accidental damage occur within the operational life of the airplane, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected. FAR 25.571 effectively addresses all models certified after 1978. However, thousands of aircraft in service today were certified fail-safe before 1978 and are not required to comply with these damage tolerance guidelines. The regulatory authorities have addressed these models by challenging the industry to resolve this aging fleet concern and by releasing guidance material in the form of two ACs.

AC 91-56, "Supplemental Structural Inspection Program for Large Transport Category Airplanes," provides guidance material to be used to develop a continuing structural integrity program to ensure safe operation of transports not certified damage tolerant under current FAR 25.571. This AC defines the structure to be evaluated, the type of damage considered (fatigue, corrosion, service, and production damage), and the inspection and/or modification criteria. To the extent practical, this guidance material is in accordance with the damage tolerance principles of the current FAR 25.571.

AC 25.1529-1, "Instructions for Continued Airworthiness of Structural Repairs on Transport Airplanes," provides instructions to ensure continued airworthiness of repaired structure. This AC affects structure certified damage tolerant per FAR 25.571, Amendment 25-45, and airplanes certified fail-safe with Supplemental Inspection Documents satisfying the intent of AC 91-56.

A revision to AC 91-56 is expected in the near future to provide guidelines to perform a widespread fatigue damage assessment. An industry committee has drafted this revision and submitted it to the FAA.

INDUSTRY COMMITMENT TO SAFETY—MEETING THE CHALLENGE

Most people within the commercial airplane inustry know that a very significant effort was initiated in 1988 to address aging airplanes. This industrywide effort is substantial and will be discussed in detail in this paper, but 1988 was not the start of fleet safety concerns. Boeing and other manufacturers have always been committed to the design, manufacture, and in-service support of safe commercial jet transport. Boeing, for example, has demonstrated this commitment over

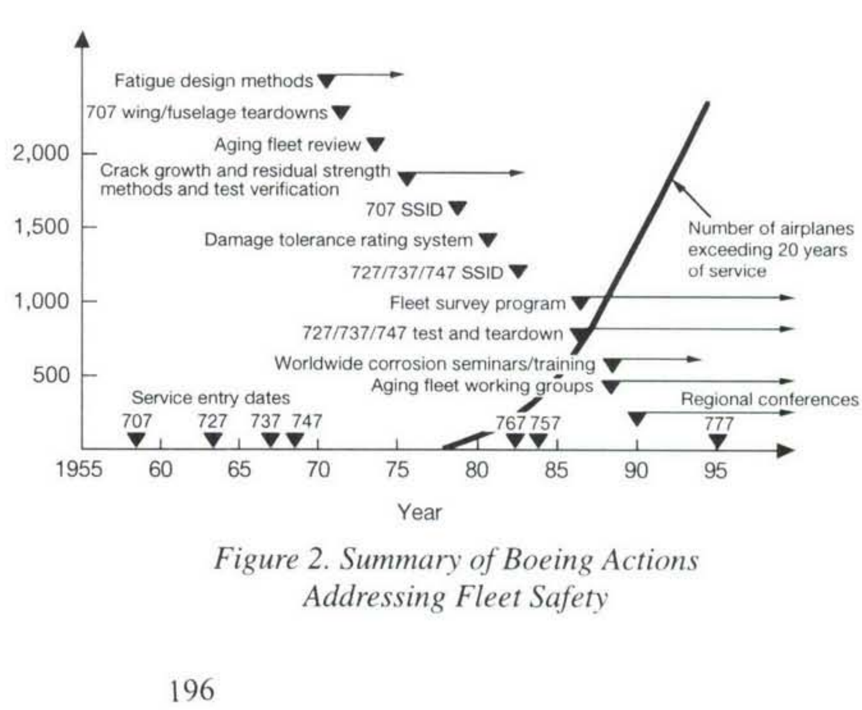


Figure 2. Summary of Boeing Actions Addressing Fleet Safety

the past 25 years by dedicating tremendous resources to identifying potential problems and developing methods to address these concerns. The most significant of these actions are illustrated on figure 2 and summarized here.

Fleet Support

To promote safe and economic operations of the worldwide fleet, Boeing has always reviewed reported service data and other firsthand information from customer airlines. This activity has resulted in production changes and updates to the inspection and overhaul recommendations contained in maintenance manuals and service bulletins.

Supplemental Structures Inspection Program (SSIP)

SSIPs were developed by Boeing in the late 1970s and early 1980s to address fatigue crack detection in airplanes designed and certified to fail-safe principles. This program requires operators to regularly inspect principal structural elements (structurally significant items) on selected high-flight-cycle airplanes and report the defects to Boeing. Fleet action is implemented as required to maintain the safety of the entire fleet.

Fleet Survey Program

Boeing implemented this program in 1986 to further expand existing Boeing knowledge of aging airplanes and those factors influencing maintainability of structure and systems. The specific objectives of this program are to:

- Gain an engineering assessment of the condition of older airplanes.
- Observe the effectiveness of Boeing corrosion prevention features.
- Acquire additional fleet data to be used to improve maintenance recommendations and promote better designs.

Survey teams of six experienced Boeing engineers conduct the evaluation and record their findings in a survey document unique to each model airplane. Significant findings result in appropriate fleet action.

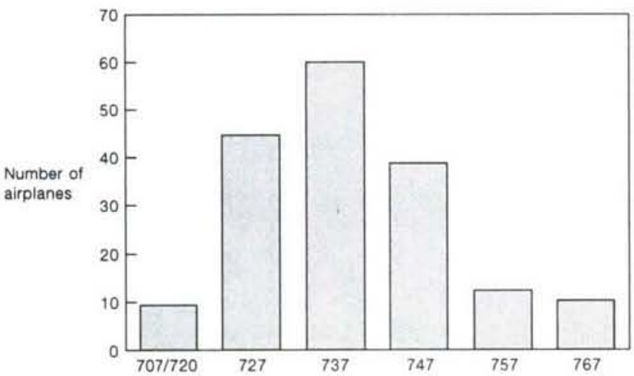


Figure 3. Boeing Fleet Survey Status

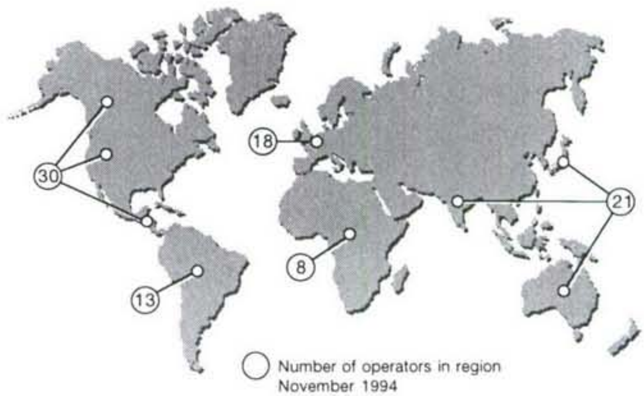
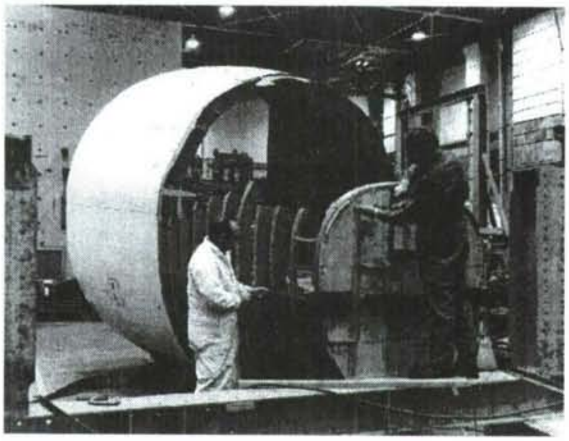


Figure 4. Boeing Fleet Survey Participants

The program was originally planned for 2 years, but because of its success, continues today. Figures 3 and 4 summarize the efforts expended to date. By June 1995, 184 airplanes were surveyed in 48 countries around the world.

Teardown Inspection Program

Since the mid 1960s, when the oldest 707s began to approach the design service objective, Boeing has conducted teardown inspections of retired high-time airplanes (fig. 5). To date, at least one high-time 707, 727, 737, and 747 has been torn down and inspected. Figure 6 summarizes these inspections. Teardown inspections permit a detailed examination of structural performance and provide useful information for forecasting future structural maintenance requirements. In addition, teardowns provide an excellent database for calibrating analysis tools such as fatigue methods.



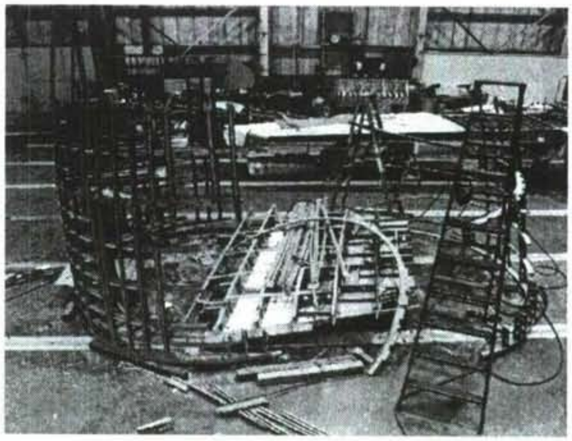


Figure 5. Teardown Inspection of a Boeing 707

- 707 wing plus center section 1965
- 707 wing 1968
- 707 wing plus center section and fuselage ... 1973
- 707 empennage 1978
- 727 forward fuselage 1978
- 737 wing plus center section, forward fuselage, and empennage 1987
- 737 aft fuselage 1988
- 747 wing and empennage 1989
- 747 fuselage 1991
- 727 wing and empennage 1994
- 727 fuselage 1995

Figure 6. Boeing Teardown Inspection Summary

Full-Scale Test Program

Full-scale static and fatigue tests are usually conducted on new models. Static tests are conducted to verify limit load-carrying capability and to satisfy certification requirements. Fatigue tests locate areas that may exhibit fatigue problems and verify inspection and maintenance procedures.

In addition to full-scale tests of new models, Boeing has recently fatigue tested the fuselage of three retired airplanes. The primary purpose of this testing is to determine maintenance recommendations for airplanes being utilized beyond their design service objective. Boeing has purchased a damaged 18-year-old 737 with 59,000 flight cycles, a retired 15-year-old 747 with 25,000 short-range cycles, and a retired 25-year-old 727 with 47,000 flight cycles. The wing and empennage of each test airplane was torn down

and inspected, while the fuselage was pressure cycled for an additional 71,000 cycles, 20,000 cycles, and 123,000 cycles, respectively, for the 737, 747, and 727 (fig. 7 shows the 747 test article). After pressure testing, the fuselage was also torn down. Findings from the 737 and 747 test are summarized in reference 2. The 727 fatigue test has just been completed, and significant preliminary findings are summarized in a latter section of this paper. Teardown of the tested 727 fuselage has just begun and is expected to be completed by mid 1996.

Figure 8 summarizes the full-scale fatigue testing done for each Boeing model.

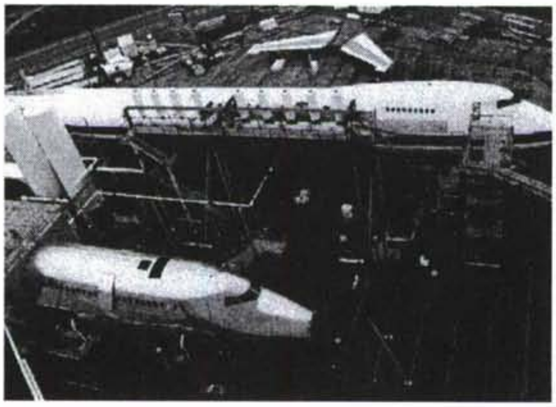


Figure 7. Retired 747 Fuselage Test Article

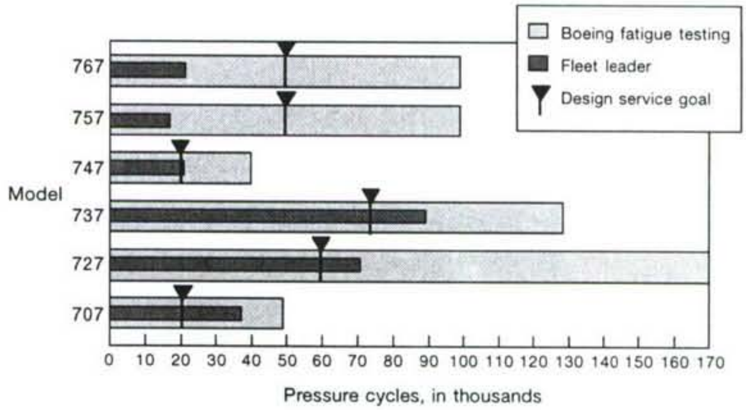


Figure 8. Boeing Full-Scale Fatigue Test

INDUSTRY COMMITMENT TO SAFETY – CONTINUING AIRWORTHINESS CHALLENGES

Industry Working Groups

In 1988, extensive industry action was initiated to address the aging fleet airworthiness concerns prompted by the explosive decompression of a 737 over Hawaii. A conference on aging airplanes was held in Washington, D.C., in June 1988. At the conclusion of the conference, a set of recommendations were published addressing aging fleet concerns. One of the recommendations was to establish a task force from the airlines, manufacturing industry, FAA, and NASA to continue the work begun at the conference. A steering committee, called the Airworthiness Assurance Task Force, now known as the Airworthiness Assurance Working Group (AAWG), made up of high-level airline, Air Transport Association (ATA), manufacturer, and FAA personnel was formed in August 1988. In late August, the AAWG formed three individual manufacturer sub-steering committees, chaired by United Airlines for Boeing, American Airlines for Douglas, and Delta Air Lines for the remaining manufacturers. These committees, in turn, chartered the individual model Structures Working Groups, now known as the Structures Task Groups (STG) (fig. 9). Each STG is composed of airline representatives, manufacturers' structural specialists, and FAA or other regulatory authorities.

Boeing STGs have met regularly in Seattle since September 1988 and have demonstrated the industry commitment to safety by their actions. Since their inception, the STGs have nearly completed the five

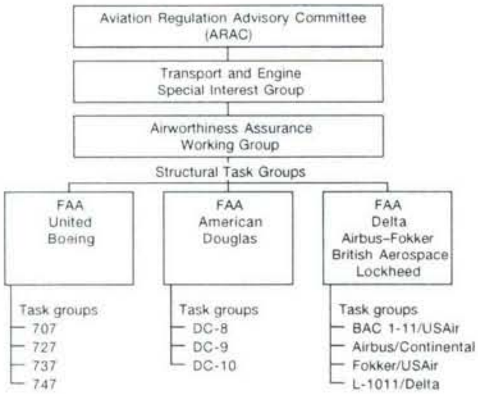


Figure 9. Industry Working Groups

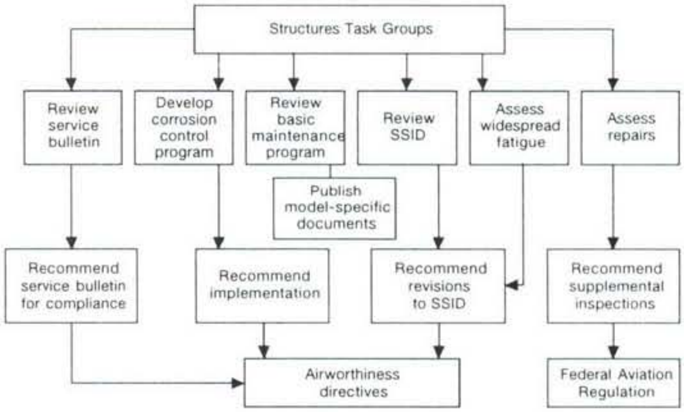


Figure 10. Industry Aging Fleet Initiatives

original tasks chartered by the AAWG (fig. 10). A sixth task, widespread fatigue damage assessment, is being addressed by AAWG and is expected to be formally chartered to the STGs shortly.

The following sections provide the current status of these six tasks. The first four tasks—service bulletin modification program, corrosion prevention and control program, basic maintenance program review, and supplemental structural inspection program—are in place today and are only briefly summarized in this paper (see ref. 3 for a detailed discussion). The remaining two tasks—repair assessment program and widespread fatigue damage assessment—are damage tolerance inspection programs currently being developed. These are discussed in considerable detail.

Service Bulletin Modification Program

Aging fleet concerns have resulted in a focus on mandatory modification rather than continued inspection of airplanes exceeding their design service objective. The Boeing Aging Fleet Survey program determined that the accomplishment of service bulletins varied with the airline and ranged from 20% to 80%. It was observed that airlines frequently chose the option, given in most service bulletins, to continue inspection rather than to perform the specified structural modification.

With age, the incidence of fatigue and corrosion increases along with the likelihood of experiencing two or more problems in one area. This is particularly true if known problems are not addressed by the incorporation of structural modifications. As a result, AAWG tasked the STGs to review all service bulletins. The emphasis of the review would be on performing preventive modifications in areas where there are potential problems, based on past experience, and where inspections may become less dependable with age.

The candidate service bulletins were reviewed by the respective STGs. The STGs selected service bulletins for modification based on the following criteria:

- Potential safety problems.
- Probability of occurrence.
- Difficulty of inspection.

The Aging Airplane Service Bulletin Structural Modification and Inspection Program documents for Boeing models 707, 727, 737, and 747 have been released. These documents summarize the recommendations of the STGs and serve as a reference for the Airworthiness Directive (AD). This program is in place; figure 11 summarizes the Boeing program documents and ADs.

Airplane Type		SB Modification/ Inspection Program		CPCP		SSID			Structural Maintenance Guidelines
Model	Series	Document	AD	Document	AD	Document	AD	Candi-dates	Document
707 720	All	D6-54996 Rev E	94-06-08 94-10-06	D6-54928 Rev D	90-25-07	D6-44860 Rev P	85-12-01	All	D6-55684 Rev A
727	All	D6-54860 Rev G	94-05-04 94-07-08	D6-54929 Rev D	90-25-03	D6-48040-1 Rev H	84-21-05	400	D6-55685 Rev A
737	-100 -200 -200C	D6-38505 Rev H	90-06-02 93-08-04 93-17-08	D6-38528 Rev D	90-25-01	D6-37089 Rev C	91-14-20	123	D6-38633 Rev A
747	-100 -200	D6-35999 Rev D	90-06-06 92-27-04	D6-36022 Rev D	90-25-05	D6-35022 Rev E	93-06-01 94-15-18	117	D6-36122 Rev A
747	SR	D6-35999 Rev D	90-06-06 92-27-04	D6-36022 Rev D	90-25-05	D6-35655 Initial	86-19-01 94-15-12	6	D6-36122 Rev A

Figure 11. Boeing Aging Fleet Program

Corrosion Prevention and Control Program (CPCP)

In the late 1970s, when Boeing was developing the SSIPs, a basic assumption was made that the existing approved maintenance programs were controlling corrosion below the level that could affect airworthiness. Therefore, the resulting SSIP inspections were developed to control fatigue damage anticipated to occur as the fleet aged. If an effective corrosion control program is not in place, the frequency and severity of corrosion will increase with airplane age and corrosion will more likely to be associated with other forms of damage, such as fatigue cracking. If this interaction is allowed, it will lead to an unacceptable degradation of structural integrity. As a result, the AAWG chartered the STGs to develop a corrosion control program.

The Aging Airplane Corrosion Prevention and Control Program documents for Boeing models 707, 727, 737, and 747 have been released. These documents provide a baseline program that can be used by any operators without a proven corrosion plan. The baseline program includes access, cleaning, inspection, and refinishing requirements necessary to control corrosion.

The CPCP is in place; figure 11 summarizes the Boeing program documents and ADs. The program is reviewed on a regular basis by the STGs for its effectiveness, and appropriate changes are incorporated into the program.

Basic Maintenance Program Review

Modern transport category airplanes were designed to meet continuing airworthiness requirements for an indefinite period. This statement is valid provided structural integrity is maintained by an effective inspection and corrective maintenance program. Comprehensive maintenance program guidelines that properly address the aging fleet did not exist in 1988. Therefore, the AAWG chartered an industry subcommittee to establish guidance material for use in developing an aging aircraft maintenance program.

The general and model-specific guidelines documents for Boeing models 707, 727, 737, and 747 have since been released. These documents, listed in figure 11, summarize all existing mandatory requirements (including those resulting from other aging fleet STG activities) as well as nonmandatory economically significant recommended maintenance actions. They provide the operator with a single source that references all significant maintenance recommendations.

Supplemental Structural Inspection Program (SSIP)

As previously discussed, the Boeing SSIPs were initially developed between 1979 and 1983 to ensure continued safe operation of the aging fleet by detecting fatigue damage before it results in unsafe structure. The program requirements were published in the Supplemental Structural Inspection Documents (SSID), which have been updated on a regular basis to reflect service experience, operator input, and damage tolerance methodology changes. In 1988, the AAWG directed the STGs to review the SSIPs to ensure that they adequately protected the aging airplanes. With this charter, Boeing STGs reviewed their SSIDs and developed a statement of work addressing the following issues:

- Candidate fleet representation.
- Choice of structurally significant items.
- Fuselage monocoque controlled decompression.
- Significant methodology improvements.
- Multiple-site cracking.
- Overdependence on secondary cracking.
- Surveillance of adjacent structure.

This statement of work has resulted in a substantial revision for Boeing models 707, 727, 737, and 747 SSIDs. Figure 11 summarizes the program documents and ADs.

Repair Assessment Program

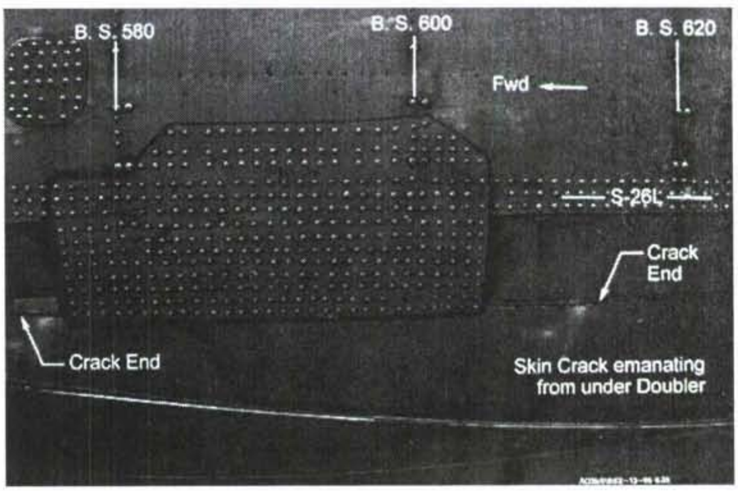


Figure 12. Fuselage Skin Crack Emanating From Under a Repair Doubler

The SSIP, previously discussed, was initially developed in the late 1970s and early 1980s to ensure continued safe operation of the aging fleet by satisfying the intent of damage tolerance requirements specified in FAR 25.571. The SSIP effectively made the "as delivered" fail-safe structure damage tolerant. Unfortunately, airplane structure is changed by the accumulation of repairs, which are inevitable in service. Most repairs on fail-safe certified airplanes were installed per the model specific Structural Repair Manuals (SRM) or service bulletins. These documents provide repairs that maintain the airframe structural integrity but, in most cases, do not address damage tolerance. Figure 12 shows a 44-in crack in the fuselage skin that initiated under a typical SRM repair doubler. This crack was found on a full-scale fatigue test article at high cycles, but illustrates the damage tolerance concern of the repaired structure.

In general, repaired structure have been kept safe by existing maintenance programs and sufficient durability resulting from pre-Amendment 25-45 design criteria. However, as the fleet ages, the need for supplemental inspection to maintain the damage tolerance of repaired structure has been recognized and the task of assessing existing repairs on aging airplanes accepted by the AAWG.

Industry Activities

To develop the repair assessment program, the AAWG chartered an industry subcommittee titled the Repair Assessment Task Group (RATG) in 1991. RATG provided many recommendations, the most significant of which were guidelines to all STGs, which have resulted in a common approach taken by the various manufacturers. This common approach will benefit the airlines who operate mixed fleets.

Repair Assessment Rule and Advisory Circular

The repair assessment program will be mandated by an operational rule change to 14 CFR Parts 91,121,125, and 129. The following rule language was drafted by an industry committee chartered by the AAWG. This draft has been approved by the AAWG and will be submitted to the FAA in mid 1995. It is currently expected that this rule will become effective in 1998.

"No certificate holder may operate a A300, BAe 1-11, B707/720, B727, B737, B747, DC-8, DC-9/MD-80, DC-10, F28, or L1011 beyond the flight cycle implementation time, or by one year from the effective date of this rule whichever occurs later, unless a repair assessment program applicable to the external fuselage pressure boundary (fuselage skin and bulkhead webs) that has been approved by the Administrator is incorporated within its maintenance program: . . ."

In addition to the draft rule, this industry committee prepared an accompanying advisory circular (see ref. 4 for details).

Program Overview

The objective of the repair assessment program is to ensure continued structural airworthiness equivalent to similar unrepaired structural elements. The priority of the program is to assess existing pressurized fuselage repairs on the 11 pre-Amendment 45 models. However, the model-specific repair assessment material published by the manufacturers can also be used to determine damage tolerance inspection requirements for new repairs.

Similar principles and guidelines may be developed to cover other structure beyond the fuselage pressure boundary. Industry activity to evaluate the need for these guidelines is expected and will be conducted in a similar fashion to the process used for the fuselage pressure boundary structure.

The implementation time for the assessment of existing repairs is based on the findings of repair surveys conducted by the AAWG and on fatigue damage considerations. The repair survey findings indicated that all repairs assessed appeared in good structural condition. It was therefore concluded that the assessment needs to be implemented before a specified model reached its design service objective (DSO). Based on this information, the industry committee recommended the repair assessment program be incorporated into an airplane's maintenance program at 75% of the DSO in terms of flight cycles, or 1 year after the effective date of the rule.

The manufacturers will provide the repair assessment guidance material in a model-specific document and SRM revision. This will allow operators to conduct the assessment of existing repairs to determine which require supplemental maintenance action beyond a specified threshold. The guidance material will also define these necessary maintenance actions.

Repair Assessment Guidance Material

Repairs may affect damage tolerance in different ways. An external fuselage skin repair, for example, may hide structure to the extent that supplemental inspections are required (fig. 13). A very similar repair located in a low-stress area may not require any supplemental inspections, because damage tolerance may be maintained by normal maintenance inspections. The objective of the STG repair assessment process is to provide a practical methodology in the form of guidance material (based on damage tolerance principles) that will allow repairs to be evaluated by operators without complex analysis. This process is directed toward showing that an installed repair, which replaces the strength and durability of the original structure, is damage tolerant if the existing inspection program is adequate. However, the assessment process will also provide inspection requirements in terms of methods, thresholds, and repeat intervals for repaired structure that requires supplemental inspections to maintain damage tolerance.

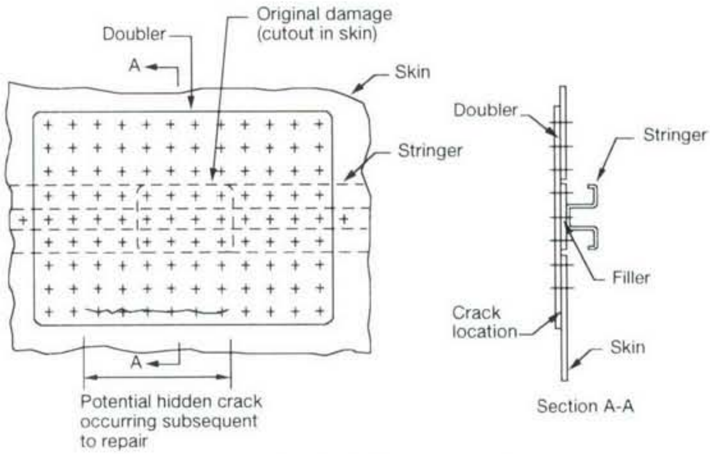


Figure 13. Typical Fuselage External Skin Repair

The repair assessment process is a three-stage procedure summarized in figure 14. This procedure can be thought of as a filtering system, where each stage filters out repairs that do not require supplemental inspections, thereby minimizing the operators' work to do the assessment.

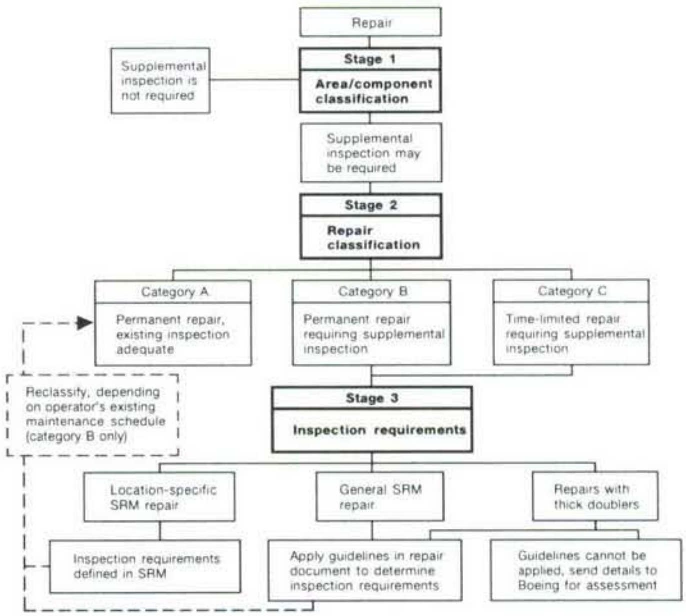


Figure 14. Repair Assessment Process

Stage 1

This stage identifies the structure that must be assessed for repairs. If a repair is installed on "structure of concern," the assessment continues; otherwise, the repair does not require classification per this program, and no further action is required.

The Boeing program uses a baseline zonal inspection (BZI), which was developed in conjunction with STG members. The BZI represents inspection intervals that most operators meet and was used by Boeing as an evaluation tool to eliminate repairs or structural areas from the program, thereby simplifying it.

The details of repairs that are not eliminated from the process in stage 1 are collected for further analysis in stage 2. Optional questionnaires provided by the model-specific documents make this task simple.

Any repairs that do not meet static strength requirements must be reworked or replaced before further flight. Because existing regulations apply, no specific categorization is required for such repairs. Repair condition and design criteria questions in stage 2 define the minimum standards to aid the operators make this determination.

Stage 2

Repairs are categorized in this stage by using the data gathered in stage 1 to answer simple questions regarding structural characteristics. A Repair Classification Questionnaire provided in the model-specific document is used to categorize each repair as A, B, or C:

- Category A: A permanent repair for which the BZI is adequate to ensure continued airworthiness.
- Category B: A permanent repair that requires supplemental inspections to ensure continued airworthiness.
- Category C: A temporary (time-limited) repair that requires rework and supplemental inspections to ensure continued airworthiness.

Well-designed repairs, in good condition and meeting size and proximity requirements, are category A and do not require supplemental inspections. The assessment of these repairs stops at this stage. Other repairs are category B and C and require supplemental inspections to maintain the structure's damage tolerance. The assessment of these repairs continues to stage 3.

Stage 3

The supplemental inspection and/or replacement requirements for category B and C repairs are determined during this stage. Inspection requirements for repairs are determined by simple calculation or by using predetermined values. See figure 15 for an example used in the Boeing model-specific documents.

Incorporating the resulting supplemental inspection requirements into the operators' maintenance program completes the repair assessment process.

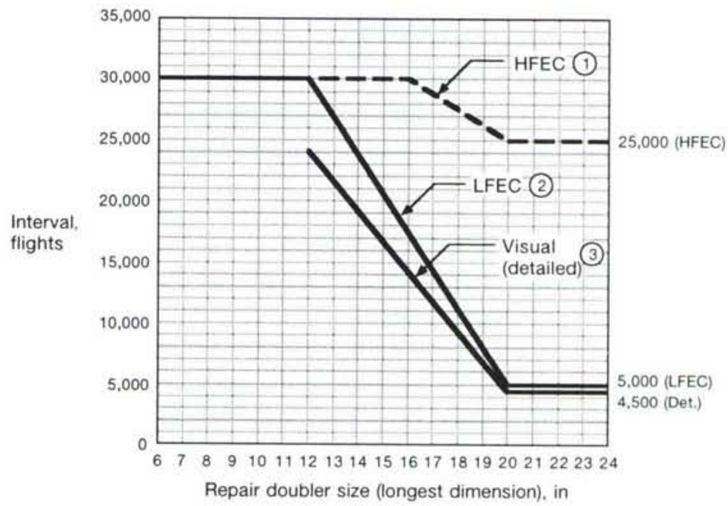


Figure 15. Example of Boeing Fuselage Repair Inspection Requirements

Structural Repair Manual Updates

Model-specific Structural Repair Manuals (SRM) will be updated by the manufacturers to reflect damage tolerance repair considerations and will be FAA approved in accordance with current practice.

The general section of each SRM will contain an overview of the repair assessment program. Specific fuselage pressure boundary structure repair instructions will provide repair categories and related information. Generic pressurized fuselage structural repair instructions will contain guidelines to determine the repair category considering its size, zone, and proximity to other repairs. Detailed information for the determination of inspection requirements will be provided in the separate guidance material for each model.

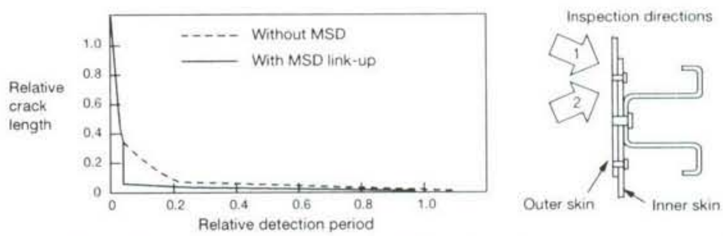
Program Status

The STGs and Boeing have worked together to develop the repair assessment program. The STG objective of developing guidance material that allows the operator to evaluate existing repairs without complex analysis has been accomplished, and the program is currently in the final phase of STG review. Boeing plans to distribute the guidance material in late 1995 to support the upcoming rule change.

Widespread Fatigue Damage (WFD) Assessment

Commercial jet transport in service today have not become technologically obsolete as have airplanes in the past. As a result, many of these aging airplanes are flying past their original design service objective. In this environment, the likelihood of experiencing multiple-site damage (MSD) in the fleet is increased significantly.

MSD has recently been addressed by the AAWG. As previously discussed, the SSID programs have been revised to address the occurrence of MSD. Figure 16 illustrates the type of change implemented in the SSID as a result of this action. Unfortunately, this action does not completely address the industry WFD concern. The SSID revision adequately addresses what has been labeled "local" MSD, which is characterized by retention of residual strength capability after link-up of adjacent cracks. The SSID does not address "independent" MSD, which reduces the residual strength and corresponding critical crack length substantially. This difference between "local" and "independent" MSD is further illustrated in figure 17.



Inspection direction	Inspection method	Cracking pattern	Interval	Detection probability/DTR
1 (external)	Detailed visual	With MSD link-up	C-check	0.86/3
		Without MSD	C-check	0.999/11
2 (external)	HFEC	With MSD link-up	4C-check	0.999/10
		Without MSD	4C-check	0.999/12

Figure 16. Example of SSID Revisions to Account for Assumed MSD Link-up in Lap Splices

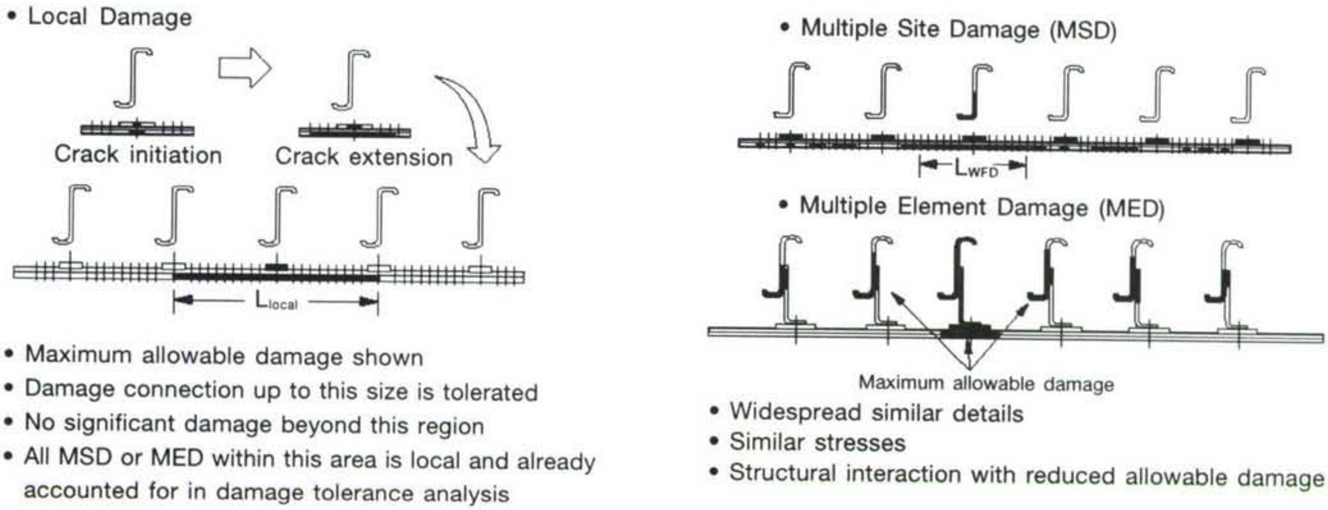


Figure 17. Example of Local Versus Widespread MSD or MED

WFD Concern

Widespread fatigue damage in a structure is characterized by the presence of multiple structural details with cracks that are of sufficient size and diversity whereby the structure will no longer meet its damage tolerance requirement (e.g., maintaining the required residual strength after partial failure); see figure 18. There are two distinct types of WFD:

- Multiple-site damage (MSD): Simultaneous presence of fatigue cracks in the same structural elements.
- Multiple-element damage (MED): Simultaneous presence of fatigue cracks in adjacent structural elements.

WFD is a concern when a large region of structure with similar details operates at the same significantly high stress level. Coalescence of multiple damage origins may potentially be catastrophic, and there is a lack of confidence in damage detection before such unsafe conditions may develop. Figure 19 illustrates the impact widespread damage has on the allowable (or critical) crack.

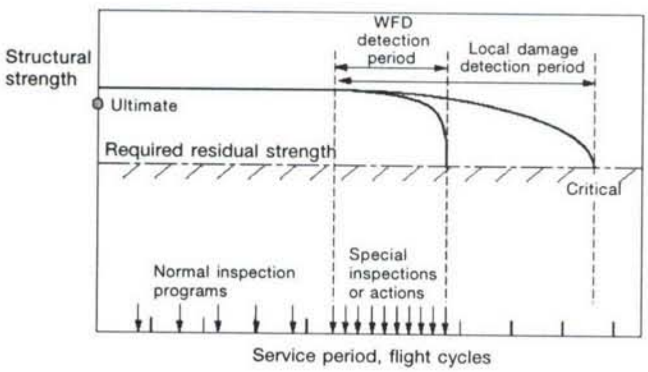


Figure 18. Damage Detection Comparison–Local Versus Widespread Fatigue Damage

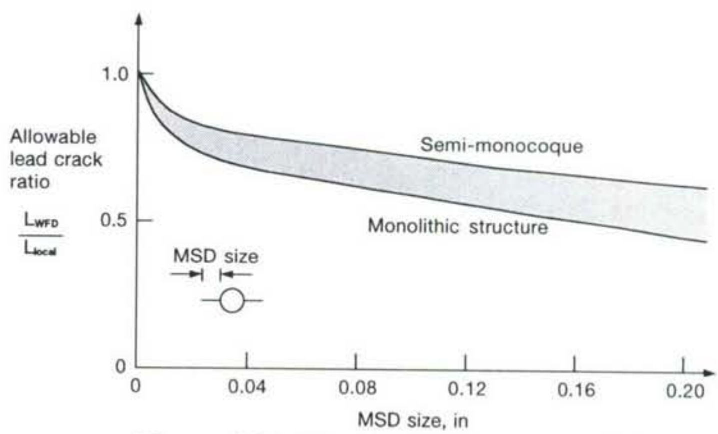


Figure 19. MSD Influence on Allowable Lead Crack Size

Industry Activities

An international task group, comprising manufacturers and operators, was chartered in 1990 to investigate and propose appropriate actions to address the WFD concern. The task group summarized their conclusions in a report released in 1991 (ref. 5). They concluded that significant improvements in the structural safety system have been introduced by AAWG-sponsored initiatives (fig. 10); however, there is still an outstanding concern for the potential onset and possible nondetection of widespread fatigue damage. Model-specific audits were therefore proposed for those airplanes that have exceeded or are approaching their original design service objectives.

In June 1991, the FAA accepted this proposal in principle, but some concerns existed that a specific rule may be necessary. The AAWG was informally tasked to consider whether new requirements for WFD evaluations and corrective action should be initiated. In October 1993, the AAWG recommended the following approach be adopted for WFD evaluation and prevention (ref. 6):

- AAWG to promote WFD evaluation in the STG environment.
- AC 91-56 be modified to include WFD evaluation guidelines.
- STGs to recommend appropriate fleet action through SSIP or service bulletin modification program.
- AAWG to monitor WFD evaluation.
- Mandatory action should enforce STG recommendations.
- Additional rule making not necessary for aging airplanes.
- Additional action for in-production airplanes should only be considered after aging airplanes evaluation completed.

To support these recommendations, the AAWG provided the following (ref. 6):

- WFD evaluation guidelines (proposed draft of AC 91-56 revision), summarized in figure 20.
- A list of structure susceptible to WFD, summarized below.
- Letters of commitment from each manufacturer to do the WFD evaluation.

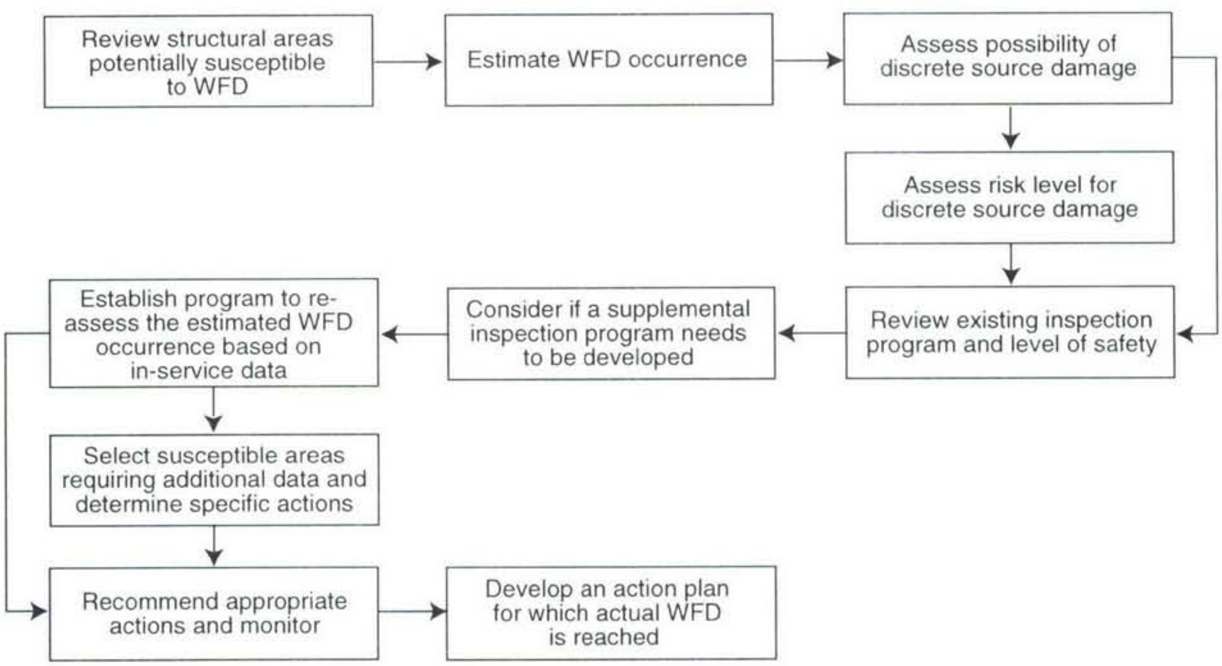


Figure 20. WFD Evaluation Process

Structure Susceptible to WFD

Structure susceptible to WFD has the characteristics of similar details operating at similar stresses where structural capability could be affected by interaction of similar cracking. Thirteen types of structure potentially susceptible to WFD have been identified. This list is the result of comparing and classifying the overall full-scale test and in-service experience of all manufacturers. The following structures are identified as potentially susceptible to WFD:

- **Fuselage.**
  - Longitudinal skin joints, frames, and tear straps.
  - Circumferential joints and stringers.
  - Frames.
  - Aft pressure dome outer ring and dome web splices.
  - Other pressure bulkhead attachment-to-skin and web attachment-to-stiffener and pressure decks.
  - Stringer-to-frame attachments.
  - Window surrounding structures.
  - Overwing fuselage attachments.
  - Latches and hinges of nonplug doors.
  - Skin at runouts of large doublers.
- **Wing and empennage.**
  - Chordwise splices.
  - Rib-to-stiffener attachments.
  - Skin runouts of large doublers.
  - Stringer runouts at tank end ribs.

Program Status

The AAWG has not formally tasked the model-specific STGs to evaluate the aging airplanes for widespread fatigue damage. However, as previously stated, all manufacturers have committed to voluntarily do a WFD assessment of the susceptible areas summarized above. Boeing is honoring this commitment and is currently evaluating our fleet for WFD.

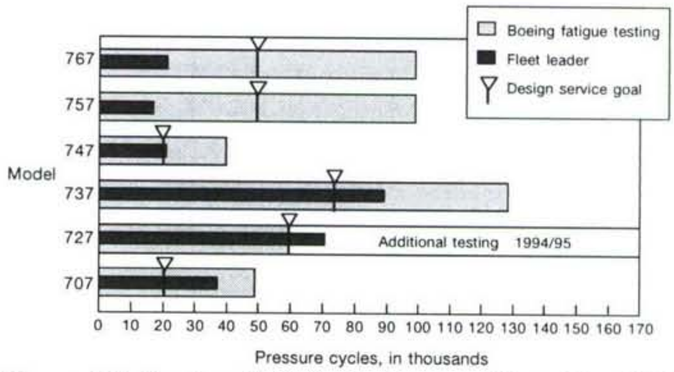


Figure 21. Boeing Full-Scale Fatigue Test–May 1993

WFD analysis methods are currently limited; therefore, Boeing is currently assessing structure with our existing damage tolerance tools and conservative simplifying assumptions. At the same time, we continue to expand our test database to support the model-specific WFD assessments and methodology development.

In recent years, Boeing has committed significant resources to fatigue test and teardown of aging airplanes beyond their DSOs. This effort supports a commitment to maintain the safety of the aging fleet and is particularly valuable to supporting the WFD assessment. Reference 2, "Performance of Fuselage Pressure Structure," summarizes the fatigue testing completed by 1991, with particular attention to MSD cracking.

Figure 21 summarizes the status of Boeing full-scale fatigue test as of May 1993. At this time, the 727 testing lagged behing that of the other models. In support of the WFD assessment program and a commitment to the industry to maintain safety of the aging fleet, Boeing decided to conduct additional testing of the 727. As had been done with the 737 and 747, a retired 727 airframe was purchased for additional fatigue testing and teardown inspections.

The airplane was purchased with 47,000 flight cycles. The wing and and empennage structure received a selective teardown inspection, with no additional fatigue testing. The fuselage was subjected to an additional 123,000 pressure cycles and will soon undergo its teardown inspection. Fatigue testing was limited to the fuselage because it is most susceptible to WFD. The fuselage has large areas of identical structure subject to pressure cycle loads with moderate flight-by-flight variations. Hence, the possibility of initiating WFD is greatest on the fuselage.

The pressure testing has just been completed, and the teardown inspections are just getting under way, so it is too early to summarize the test findings as was done in reference 2. However, a number of cracks with potential impact upon the WFD program were experienced in the fuselage and are summarized here:

- Lower lobe frames (fig. 22).
- Lap splice lower fastener row (fig. 23).
- Skin at typical stringers (fig. 24).

Each of these areas will be studied carefully during the teardown inspection. Fleet action to address WFD concerns in these areas will obviously be dependent on our findings and on the resulting WFD analysis.

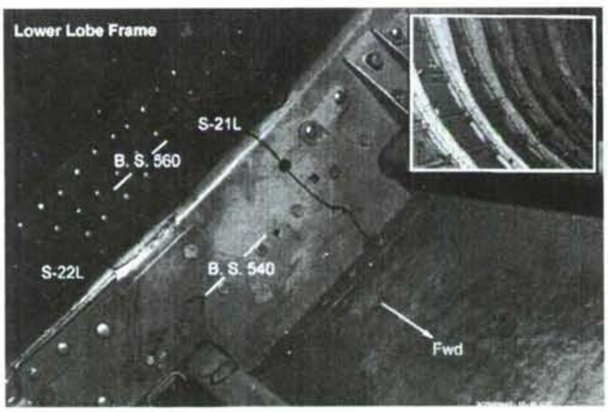


Figure 22. Typical Forward Lower Lobe Fuselage Frame Crack

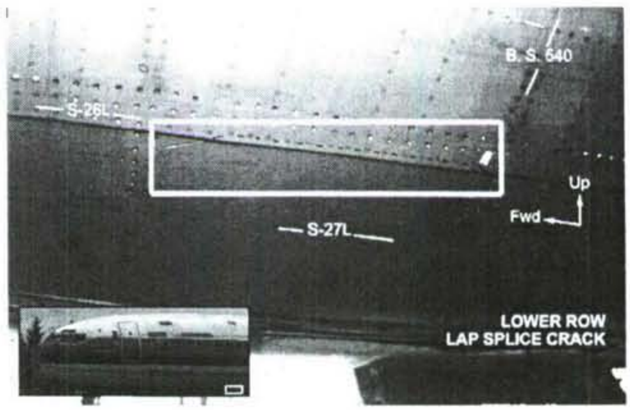


Figure 23. Twenty-Inch Lap Splice Crack Common to Lower Fastener Row

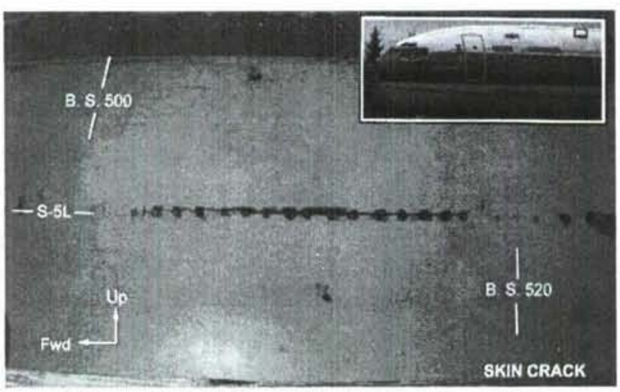


Figure 24. Fifteen-Inch Fuselage Skin Crack Along Typical Stringer

SUMMARY

The airline industry has always been committed to maintaining fleet safety and has an excellent record as a result. In recent years, this commitment has led to the formation of industry working groups that have been responsible for the development of a number of new programs addressing the aging fleet. The achievements of these industry groups have been impressive but their task is not complete. The repair assessment and widespread fatigue damage assessment programs, currently in work, must be completed and all necessary fleet action implemented. When this is accomplished, the aging fail-safe certified airplanes will be damage tolerant and the regulatory challenge satisfied.

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ACKNOWLEDGEMENTS

The author would like to acknowledge the graphics and publications support from Mr. W. J. Brewer and from Boeing Communication Services.

MEETING THE REQUIREMENTS FOR STRUCTURAL REPAIRS AND RECORD KEEPING IN AN AIRLINE

Bert Hoogeland
747 Structures Engineering
KLM Royal Dutch Airlines

This paper will focus mainly on the way VERAMIS is used to record and manage repair information and the planned developments to extend the functionality of this system. A detailed description of VERAMIS will be skipped since this has been presented at earlier conferences and since there are brochures available describing the system.

KLM ENGINEERING & MAINTENANCE

KLM Engineering & Maintenance is the maintenance division of KLM Airlines. KLM Engineering & Maintenance is located at Schiphol-East in the Netherlands and is a separate business entity from the airline. The maintenance division has an annual output of approximately 4.0 million man-hours and has performed third party work since 1947. Aircraft Maintenance Services is provided for:

- Boeing 737 and 747
- McDonnell-Douglas DC-10 and MD-11
- Airbus A310

KLM Engineering & Maintenance has performed more than 150 heavy maintenance visits on Boeing 747s. Furthermore KLM Engineering & Maintenance performs overhaul on General Electric CF6 engines and aircraft components.

PRESENT SITUATION REPAIR ASSESSMENT PROGRAM

The upcoming Repair Assessment Program was one of the reasons for KLM to start with VERAMIS (VEhicle Repair And Maintenance Information System).

Since 1988, when discussion about a Repair Assessment program started, the intended scope of the program has changed. Initially the Repair Assessment was to be performed on the complete

aircraft structure (internally and externally) with a compliance period of approximately 4 years. Later on the indications about the required compliance period changed to 15.000 cycles or the next major check (for 747s). The area to be assessed for existing repairs has for the 747 changed to the fuselage pressure boundary.

REPAIR REGISTRATION USING VERAMIS

VERAMIS features a relational database integrated with a 3D model of the aircraft. VERAMIS has been built around Intergraph hardware and standard software and was developed in partnership by KLM and Intergraph.

The VERAMIS database stores all relevant information for structural repairs such as installation date, location, approval data, repair drawings, and more. The repair information is stored behind repair markers linked to the three-dimensional (3D) model in VERAMIS. Repair drawings are drafted in two dimensions (2D) in the VERAMIS CAD system based on scanned-in production drawings.

KLM uses five work-stations, a scanner, a 36-inch plotter, and a server as main hardware items to run VERAMIS.

Within KLM it was decided to have mechanics/inspectors do the inspections to find existing repairs and to have engineers perform the Repair Assessment.

Presently KLM uses VERAMIS to record all relevant information on new repairs. Existing repairs are assessed during opening-up of areas for CPCP inspections. Assessing existing repairs consists of collecting all relevant repair data and storing the information in VERAMIS.

Repairs are not yet being classified since the actual classification of repairs is not yet possible for the 747. This is because the 747 Structural Repair Manual (SRM) does not yet contain the required information to do the classification in A-, B-, C-, or D-type repairs.

BENEFITS OF VERAMIS

Benefits of VERAMIS are efficient record keeping, reporting, and drafting of repair drawings. Further, 3D presentations in VERAMIS offer optimum access to the repair information. This is very useful for quick response to production requests for repair solutions and when information should be provided during selling of an aircraft, for audits, and so on.

Another option in VERAMIS is making selections from the information in the database. This can be used when a modification or the corrosion program performance has to be evaluated.

FUTURE DEVELOPMENTS WITH VERAMIS

Work has been started to combine the VERAMIS database with a database containing all structural inspection findings (500,000 records for the Boeing 747). The nonrepair related information will not be linked by repair markers to the 3D model. Combination of the two databases will improve the possibility to do evaluations for modifications, corrosion program performance, and so on. Also the efficiency of record keeping and reporting is improved by using one database instead of two.

VERAMIS will be connected to the Boeing REDARS (Reference Engineering Data Automated Retrieval System). By using the Boeing REDARS, the airlines can have the Boeing manufacturing drawings on-line available via a network connection with Seattle. Connecting VERAMIS to REDARS will improve the efficiency of drafting repair drawings since this will eliminate scanning-in of production drawings from paper copies.

Until now all the information on repairs and other structural inspection findings was supplied to engineering on paper. More and more of this information is fed by the mechanics/inspectors to a production planning and preparation system in electronic format. Linking VERAMIS to the production planning system will eliminate double input of the data. In addition to this, selection criteria can be built into the system to check for completeness of the supplied information. Also the reliability of linking the inspection findings to its original inspection can be improved.

KLM Engineering & Maintenance is planning to incorporate an integrated data management application to manage the flow of data between authorities, manufacturers, vendors, and the airline. Undoubtedly the functions of VERAMIS and this system will be combined or connected.

SUPPORTING THE CONTINUED STRUCTURAL AIRWORTHINESS OF THE JETSTREAM 31 COMMUTER AIRCRAFT THE RULES AND BEYOND

Michael W. G. Bradley, MSc
Chief Stress Engineer
Jetstream Aircraft Ltd.
Prestwick International Airport
Scotland

ABSTRACT

In response to the Aviation Safety Act of 1991, Notice of Proposed Rulemaking (NPRM) 93-14 was issued in October 1993. This, for the first time, included commuter aircraft in the aging aircraft program.

While the actual rule has yet to be finalized, Jetstream Aircraft Limited have undertaken a program of work, in coordination with the Federal Aviation Administration (FAA) and Civil Airworthiness Authority (CAA), in order to ensure the continued structural airworthiness of the Jetstream 31.

The paper explains the work that has been done in four main areas:

(a) Review of Service Bulletins, etc.

(b) Fatigue and Damage Tolerance

(c) Corrosion Prevention and Control

(d) Assessment of Repairs

The methodology and data used in this work is presented, together with examples, and the results are discussed. Possible future work to support the continued operation of the aircraft beyond operational life limit is also described.

INTRODUCTION

The now famous Aloha incident in 1988 caused the FAA to reappraise its aging aircraft program and, among other actions, to extend it to commuter aircraft between 6000 and 75000 lb.

maximum takeoff weight. The Aviation Safety Act of 1991 required the FAA to initiate rulemaking to this effect in parallel with further actions regarding large transport aircraft. A Notice Of Proposed Rulemaking was issued in October 1993 to achieve this end (NPRM 93-14). To date the final rule has yet to be issued.

Jetstream Aircraft Ltd. (Jetstream) has, however, been working, in cooperation with the FAA and CAA, to ensure the continued structural airworthiness of the Jetstream 31.

This paper explains the scope of the work undertaken, the methodology and data employed, and the results obtained. Examples of some of the work undertaken are given where appropriate. Finally a means of extending the operational limit of the aircraft beyond that currently proposed is discussed.

HISTORY OF THE AIRCRAFT

The Jetstream 31 first flew in 1982 and remained in production until 1988. A total of 206 were delivered before it was replaced by the Jetstream 32.

The structure, however, was almost identical to that of the Jetstream Mk. 1 which was certificated in 1969.

Figures 1 and 2 show the current utilization of the world fleet in landings and years, respectively. These show, in terms of landings at least, the aircraft qualifies as an aging aircraft, the original design life being 30,000 landings.

STRUCTURAL DESCRIPTION

A general view of the aircraft appears on figure 3. It can be seen that, in the majority of areas, the layout is of a conventional design, including damage tolerant features. Stress levels were kept low to give good fatigue properties (ultimate stress in wing structure was restricted to 45,000 lb./in^2 and 2 delta P stress in the fuselage was restricted to 30,000 lb./in^2) and the materials used were mainly 2014 aluminum alloys, also giving good fatigue performance.

There is, however, one exception to this general rule. The wing bending moment is transferred through the fuselage by a single main spar with mass spar booms. While inspections using nondestructive testing (NDT) techniques are practical in the spar booms over most of their length, this is not the case at the wing to fuselage joint. The layout of the joint is shown on figure 4. The joint is of the scarf type with a large number of bolts. Fatigue testing showed that failure occurred from a relatively small crack (about 0.35 inch radius corner crack) at a bolt hole. In order to detect this crack before failure, NDT inspections requiring removal of the bolts would be needed. This has been judged to be impractical, both with regard to cost and from the point of view that bolt removal could in itself be a damage source. Thus, the joint, for the present, is considered to be in the safe-life category.

INITIAL DISCUSSIONS WITH CAA AND FAA

An initial meeting was hosted by the CAA, acting on behalf of FAA, at Gatwick in March 1991. This was attended by UK manufacturers with significant fleets in the US. At this meeting, the concerns of the Authorities regarding aging commuter aircraft were discussed at length and four main areas of action identified.

(a) A review of structural Service Bulletins (SBs), Airworthiness Directives (ADs) and Service Information Letters (SILs).

(b) A Fatigue and/or Damage Tolerance Re-evaluation.

(c) Provision of a Corrosion Prevention and Control Program.

(d) Assessment of Repairs.

Jetstream recognized the legitimate concerns of the authorities and decided to instigate work immediately rather than await the issue of a rule on the subject. The work that has been undertaken since then and the results obtained are described in more detail in the following pages.

REVIEW OF SERVICE BULLETINS AND AIRWORTHINESS DIRECTIVES

Between March and July 1991, Jetstream reviewed the existing service information documentation with the following aims.

(a) To compare FAA and CAA ADs on the aircraft to see if any existing CAA ADs should be made into an FAA AD. There were, at that time 19 FAA ADs on the aircraft and 35 CAA ADs with no equivalent FAA AD.

(b) Review Non-Mandatory Service Bulletins and Service Information Letters to see if any should have their status upgraded to Mandatory. This exercise required the review of 51 SBs and 23 SILs using the Large Aircraft Task Force Experience Rating system. This is shown in figure 5. A rating is allocated under each of the five categories and then the individual ratings summed. If the sum produces a high number (above 10 say) the SB or SIL should be mandatory. If a low number (below 5 say) results the SB or SIL should not be upgraded. An intermediate number would require a more in depth study of the particular circumstances surrounding the SB or SIL.

(c) To clarify the situation in areas where several SBs had been issued regarding the same part or structural issue.

(d) To establish terminating actions for difficult or frequent inspections.

As part of this review SBs concerning the Flap Torque Tube Universal joint were investigated. The item is shown on figure 6. It provides a link which allows the torque tube system transmitting movement from the flap actuation jack on the center fuselage to the flap itself to negotiate the kink caused by the wing dihedral. The history of SB issue on this item is given below.

After fatigue testing of the initial components, three SBs were issued to promulgate the fatigue life: one to set the life, one to create a modification record, and one to attach a serial plate.

Following the selection of a new vendor, further testing revealed a different mode of failure and three more SBs were required: two to introduce fail-safe features and one to set an inspection for this failure mode.

After failure, on test, in the original mode a life was set for the new part requiring another SB.

Finally a redesigned joint with built-in fail-safe features and a life in excess of the aircraft design life was introduced under yet another SB.

This gives a total of eight SBs and three possible joint standards on this component.

In the short term, an SIL was issued explaining the situation and the relevance of all the SBs. After a period of discussion with Jetstream, FAA finally decided to issue an AD mandating installation of the improved design joint in order to avoid a confusing situation existing on the aircraft.

In July 1991 a meeting involving Jetstream, FAA, CAA, and selected operators took place to discuss the results of the AD and SB review. This meeting eventually resulted in the issuance of only one FAA AD and two Jetstream SILs.

The FAA is currently reviewing post-1991 SBs.

FATIGUE EVALUATION

General Description of Jetstream Activity

In August 1992, Jetstream sent representatives to the first meeting of the Small Transport/Commuter Airplane Airworthiness Assurance Working Group (SAAWG). At this meeting the concept of an Operational Limit, defined as

> "That point in the life of an aircraft where additional maintenance action is required to ensure the continued airworthiness of the aircraft principal structural elements"

was introduced and discussed by representatives of manufacturers, airworthiness authorities, and operators from all over the world.

A consensus was reached that an Operational Limit that could be extended and re-extended as long as sufficient justification could be provided, would be an effective way of dealing with fatigue aspects of the aging aircraft problem.

Discussions continued over several more meetings, enthusiastically attended by Jetstream representatives, culminating in the production of a draft Advisory Circular (AC) describing acceptable means of establishing and extending an Operational Limit.

The final meeting took place in Ottawa in February 1994.

The overriding principle of the AC was that derivation of the Operational Limit should not be restricted to one particular method, and it listed and gave guidance on the application of a range of acceptable methods which were endorsed by representatives of the FAA, JAA, Transport Canada, world manufacturers, and US operators.

While this AC has yet to be published, and indeed may never be published in its original form, Jetstream considered its contents to provide excellent guidelines on which continued airworthiness of the Jetstream 31 could be based. Thus, a range of methods from the AC were used, as appropriate, to establish an Operational Limit for the Jetstream 31.

Available Test Data

A Full-Scale Fatigue Test (FTS) was started in 1969 when the Jetstream Mk. 1 was certificated. The following test flights were achieved on major areas of structure:

Wing = 152,500 flights

Fuselage = 153,846 flights

Fin = 168,200 flights

Major component tests were also carried out and these achieved:

Tailplane = 300,000 flights

Wing - Fuselage Joint = 335,000 flights

During the test, natural fatigue damage occurred in several areas. This was monitored and crack growth recorded. Inspection thresholds and periods were derived from the results and appear in the Maintenance Schedule.

Towards the end of the fatigue test, in consultation with the CAA, artificial damage was introduced in selected areas and crack growth monitored to demonstrate the damage tolerant nature of the structure.

Finally, a series of Residual Strength Tests were performed covering the following cases:

(a) 115% of max. working pressure differential on fuselage.

(b) 100% of max. working pressure differential on fuselage + 67% ultimate flight loads.

(c) 67% ultimate flight loads with no pressure on fuselage.

(d) 80% of ultimate upbending case on wing.

(e) 67% of ultimate downbending case on wing.

(f) 67% of max. landing case on wing. (High-torque case.)

The final test was the wing upbending. Failure did not occur but further testing was not possible due to rig limitations.

After completion of the testing, critical areas of the fuselage lap joints were stripped down and examined for widespread fatigue damage. No cracks were found.

Examples of naturally occurring and artificial damage monitored on the Jetstream 31 appear below.

Example of Natural Damage - Cabin Window Surrounds

Figure 7 shows the Cabin Window Surrounds on the Jetstream 31. Late in the FTS program (around 120,000 test flights) cracks started to appear in the window pans. These were all

detected by visual inspection, at or before the crack reached from the edge to the first attachment, as shown in figure 7.

In all, 12 pans were found cracked during the test, some with multiple cracks. The damage was left in place in all cases and crack growth monitored.

The following observations were made:

(a) The pan always cracked first.

(b) Crack growth in the pan is slow.

(c) Crack growth in the skin is very slow or nonexistent while the pan is intact.

(d) When the pan fails, crack growth in the skin is rapid to the next frame.

In order to avoid any problems which might exist due to interaction of cracks at adjacent frame bays, the critical point was taken as failure of the pan.

Using the average time from detection, of a crack from the first rivet hole to the edge, to failure of the pan, or end of test, an inspection period of

6,558 flights

was derived using a factor of 3.0.

The inspection period in the current Maintenance Schedule is

4400 flights.

This is to fit in with current check periodicities.

Example of Artificial Damage - Fuselage Skin Panels

In order to demonstrate the damage tolerance properties of the Jetstream 31 fuselage basic construction, the following test was carried out.

At frame 304.5 inch, between stringers at 14° and 21° (the thinnest and most highly stressed area of the fuselage skin) the frame was cut through and a crack of two inch length either side of it cut in the skin. This is shown in figure 8.

One thousand eight hundred pressure cycles equal to the maximum working pressure differential were applied, generating very little growth.

The skin crack was then extended to four inches either side of the frame by saw cut. A further 1500 cycles were then applied giving the growth shown on figure 8. This was followed by a residual strength test to 115% of the maximum working pressure differential. Very little extension of the crack resulted from this.

After a further 360 cycles, the residual strength test was repeated with the same result.

The specimen was again cycled up to a total of 4425 cycles. By this time the total crack length had reached sixteen inches. A further residual strength test did not produce failure.

After this point it became steadily more difficult to maintain pressure in the fuselage, which was being tested in a water tank, owing to leakage through the crack and the test was abandoned. A critical crack length of sixteen inches and a realistic inspection period had, however, been demonstrated.

Original Fatigue Life

Under the original UK certification rules (B.C.A.R. Section D/K), the fatigue life of the whole airframe had to be demonstrated. (This did not apply in the US as, at the time, only the fatigue life of the wing and the pressure cabin were required to be substantiated.)

Taking a safe-life approach, the fatigue life was declared at 30,000 landings using a safe-life factor of 5.

Proposed Operational Limit

Based on the crack growth and residual strength testing that had been done on the full-scale fatigue test, it was agreed with CAA that all areas of the wing, fuselage, and fin, with the exception of the wing-fuselage joint, could be classed as damage tolerant.

This allowed an inspection threshold of

life to detectable crack/3.3333

and an inspection period of

(critical crack life - detectable crack life)/3.0

to be applied to areas which had sustained damage before the end of the test.

Areas not damaged at the end of the test, but still agreed to be damage tolerant, would have an operational limit of

test life/3.3333

All other areas would still have an operational limit based on the safe-life principle, giving a limit of

test life/5.0

Applying the above procedure to the Jetstream 31 gives an operational limit of

45,000 flights

based on the current test data. If the operational limit concept does form part of the aging aircraft rule this would be Jetstream's proposal as the limit for the Jetstream 31.

This is now the CAA certificated fatigue life of the aircraft.

Future Extension of Operational Limit

Maximum Possible Extension of Operational Limit

Currently there appears to be two absolute restrictions on the extension of the Operational Limit.

(a) At the end of testing, the stripdown inspection revealed no evidence of widespread fatigue damage.

Lowest test life achieved = 152,500 flights

Therefore, earliest onset of widespread fatigue damage = 152,500/2

= 76,250 flights

(b) The maximum safe-life of the wing-fuselage joint based on the tests described earlier in this paper

= 335,000/5

= 67,000 flights

It should be noted that, at current utilization rates, even the lead aircraft would take 16 years to reach this point. By that time, advances in NDT techniques and widespread damage analysis may well make further extension an economic possibility.

Extension of Operational Limit to 67,000 Flights

It has been explained earlier in the report that the vast majority of the aircraft structure is damage tolerant. Thus, an inspection program can be developed, based on theoretical analysis of those areas of structure not damaged on test together with the test crack growth results, which will allow the aircraft to remain in service up to 67,000 flights. Much of the analysis methodology can be verified by comparison with the Jetstream 31 fatigue testing and comparison with results from the Jetstream 41 fatigue tests as the structures of the two aircraft are similar in many areas.

For some operators, with operations that yield relatively benign fatigue load spectra, it may be possible to extend the Operational Limit beyond 67,000 flights based on analysis of measured flight load data.

Who Will Pay?

It is important to note that the proposed aging aircraft rule is an operational one. Thus, there is no regulatory requirement on the manufacturer to show compliance. Provision of an extension of the Operational Limit to 67,000 flights is therefore a purely commercial decision for the manufacturer.

Two precedents have occurred within British Aerospace (Jetstream's parent company),however, with respect to provision of a Supplementary Structural Inspection Document (SSID) for large turboprops.

In the case of the 748 turboprop, large numbers of aircraft were still in service and it was decided that an SSID would be provided at no cost to the operators.

In the case of the Viscount, only a few aircraft were still in service but their operators wished to keep them flying beyond their original certificated fatigue life. The remaining operators, therefore, entered a joint agreement to finance the production of a document by British Aerospace including obtaining clearance by the CAA.

CORROSION CONTROL

At the present time, most manufacturers issue a corrosion control program. It is, however, usually part of the general maintenance schedule.

The view of the authorities was that there were three problems with this situation.

(a) It was not very easy to get an overall appreciation of the corrosion control effort on the aircraft as it was hidden among a range of other structural inspections.

(b) The program could not be mandated as it was part of the Maintenance Schedule which is not a mandatory document.

(c) No specific reporting requirements for corrosion were published.

The FAA and CAA preferred solution was the creation of a Corrosion Prevention and Control Program (CPCP) in a stand-alone document which could, when the legal framework existed, be mandated.

In December 1993, Jetstream published a CPCP for the Jetstream 31. The basic aim of the document was to provide a program which would ensure that corrosion on the aircraft was kept at level 1 or better.

The CPCP provided the following data.

(a) A definition of corrosion levels and guidance on how to allocate a level to any occurrence.

(b) A corrosion inspection program. This was based on data from two sources.

  (1) Operator Experience

  (2) The MRB environmental analysis for the Jetstream 41, which has similar structure and identical corrosion protection processes to the Jetstream 31.

(c) A list of related SBs.

(d) A definition of reporting requirements.

(e) An optional recording system.

(f) Guidance on the use of water repellent fluids.

In the case of the Jetstream 31 this resulted in a much clearer and more comprehensive description of corrosion control policy and procedures. The workload for the operator was not significantly affected.

ASSESSMENT OF REPAIRS

Current Position

It has always been the aim of Jetstream to produce repairs which have equal fatigue performance to that of the surrounding structure.

As the fatigue life in a particular area has usually been defined by the worst feature in that area and, unlike the situation with large aircraft, there are not large areas of plain stringer-skin panels, this has been achieved by making any repair joints or doublers on the aircraft similar to existing joints or doublers in the same area. Typical examples of repairs have been installed on the Jetstream 41 fatigue test to verify this philosophy.

A review of the Structural Repair Manual showed that repairs advised in that document were in line with the philosophy given above.

Major repair drawings have always been informally reviewed for fatigue performance at Jetstream before the necessary stress signature is given. It was, however, recognized that there was a need to record this process more formally. Therefore, the sign-off box shown in figure 9 was introduced. The procedure is now that the drawing should be reviewed for static strength initially and the first box signed. This signature would allow the repair to be applied to an aircraft and cover it for the first twelve months. Once the drawing has received its initial signature it is then reviewed for fatigue performance and the second signature is added. The repair is now cleared for the life of the aircraft under the same inspection conditions as the surrounding structure. In most cases both fatigue and static strength can be considered simultaneously and the signatures appended together. There are some circumstances, however, when a repair is needed quickly and the fatigue calculation is more sophisticated, that some of the 12 months is needed.

The only problem left to be addressed is that of repairs not generated or authorized by Jetstream. It is quite legal in the US, for example, for an operator to approach an FAA-approved DER to obtain a repair without reference to Jetstream.

To require all operators to survey their aircraft for repairs that do not conform to the Structural Repair Manual or do not have a Jetstream repair drawing and then assess these repairs for fatigue performance, may result in a very costly and time consuming process for the operator. Further consultation with the authorities, with the aim of learning from the experience of the large aircraft group, is required on this subject.

CONCLUSION

In 1991 Jetstream viewed the FAA and CAA's proposals with regard to aging aircraft with some trepidation, fearing a large workload and further restrictions on the aircraft.

It has been found, however, that by intelligent use of existing data and close consultation with the authorities, the workload has been relatively modest and an extended operational limit for the aircraft was able to be justified. Also, improved maintenance documentation for the operator could be produced. This has been due in no small part to the willingness of the authorities to consider any legitimate approach to ensuring structural airworthiness of aging aircraft without being bound to any particular dogma.

A clear way forward can now be seen to extend the life of the aircraft to the year 2010 and possibly beyond in a properly regulated manner.

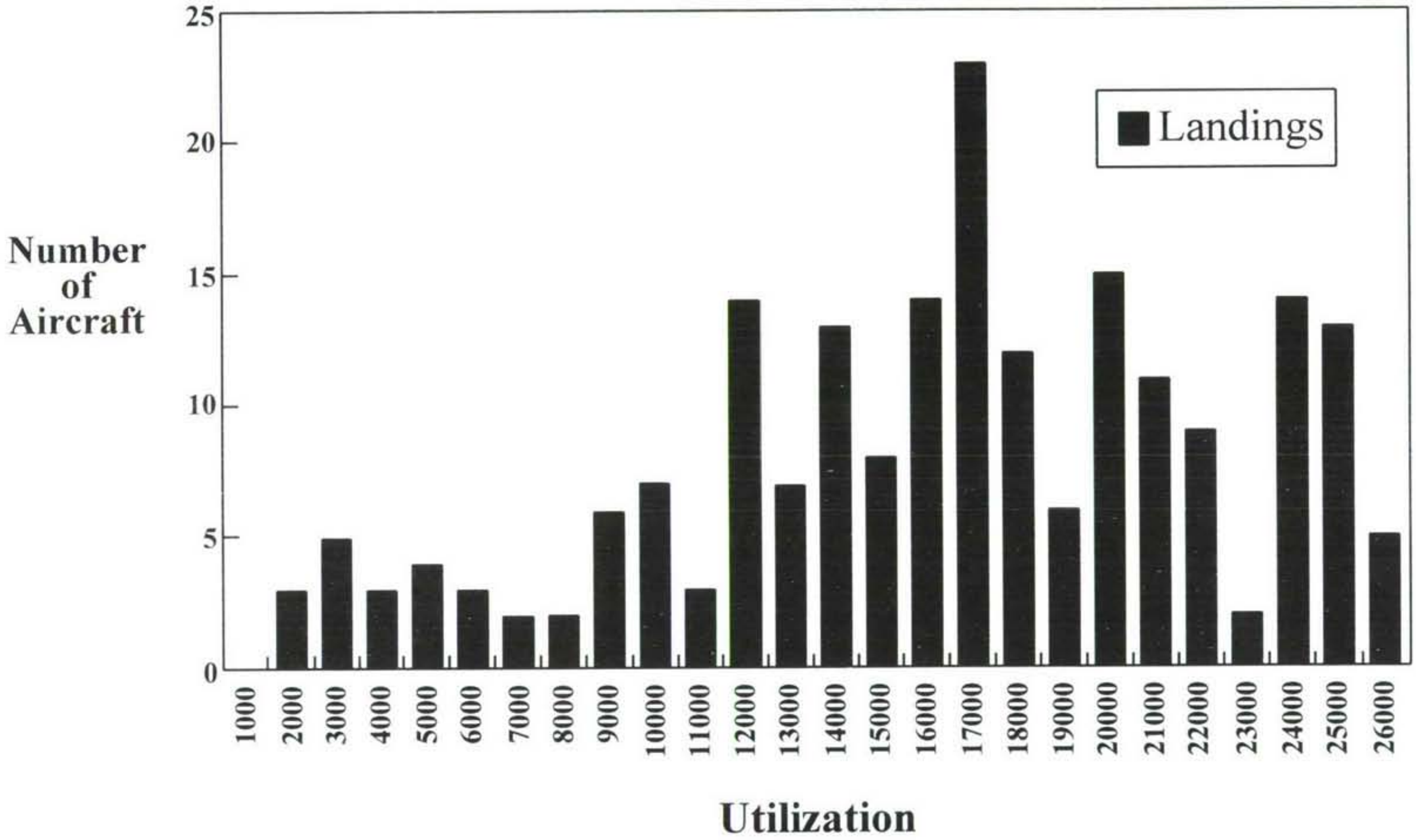

Figure 1 - Jetstream 31 Fleet Utilization in Landings

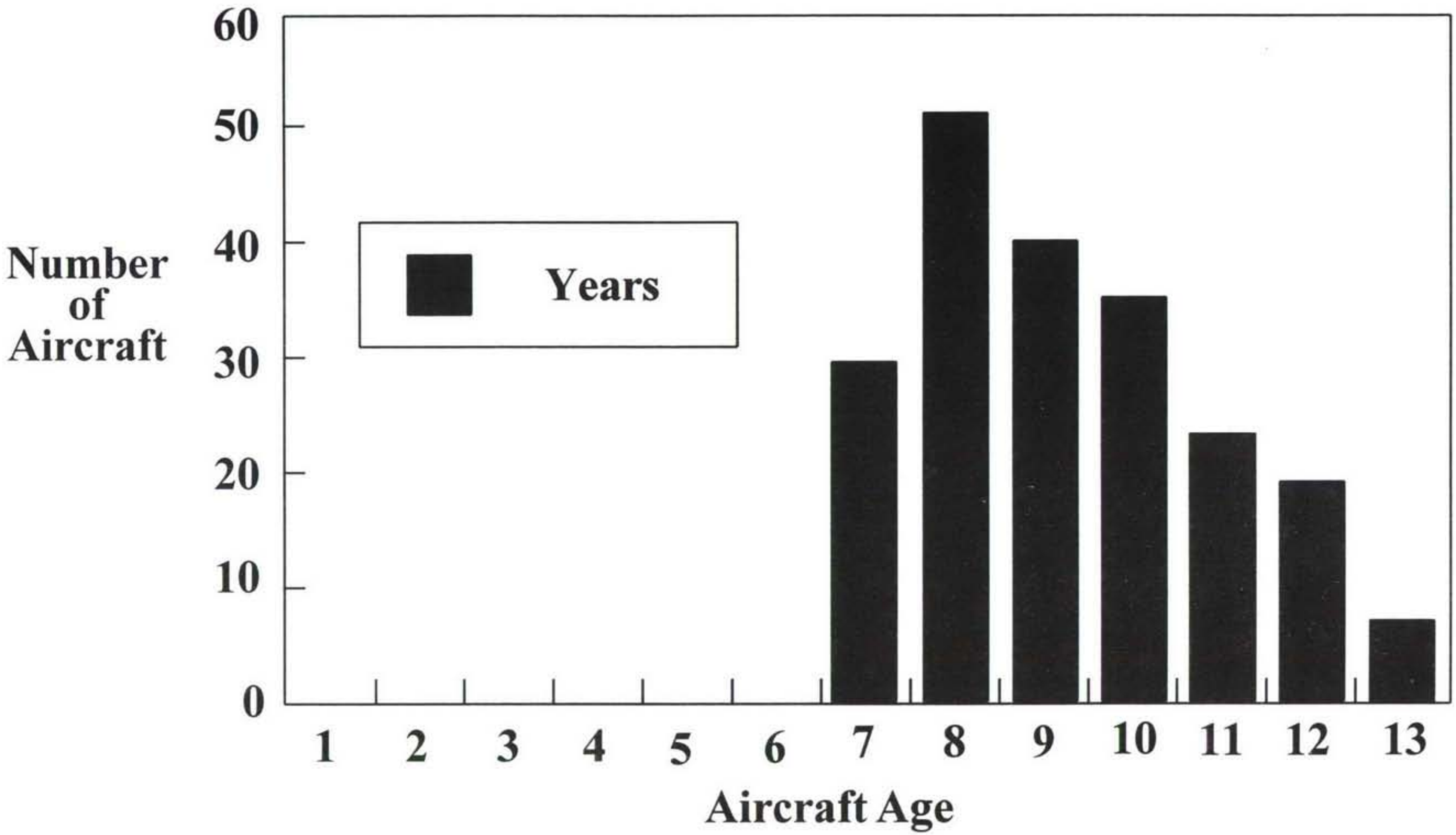

Figure 2 - Jetstream 31 Fleet Utilization in Years

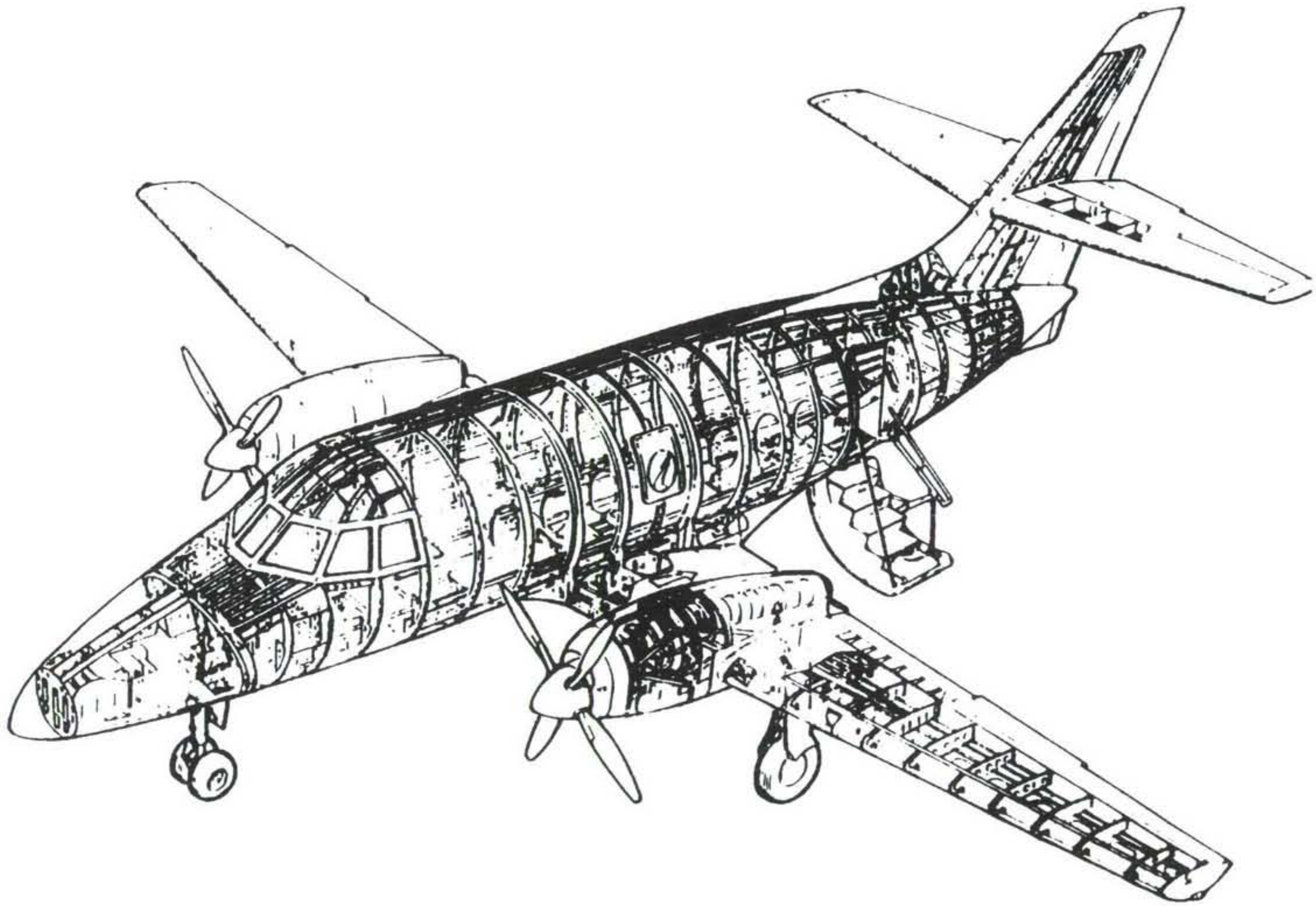

Figure 3 - General View of the Jetstream 31 Structure

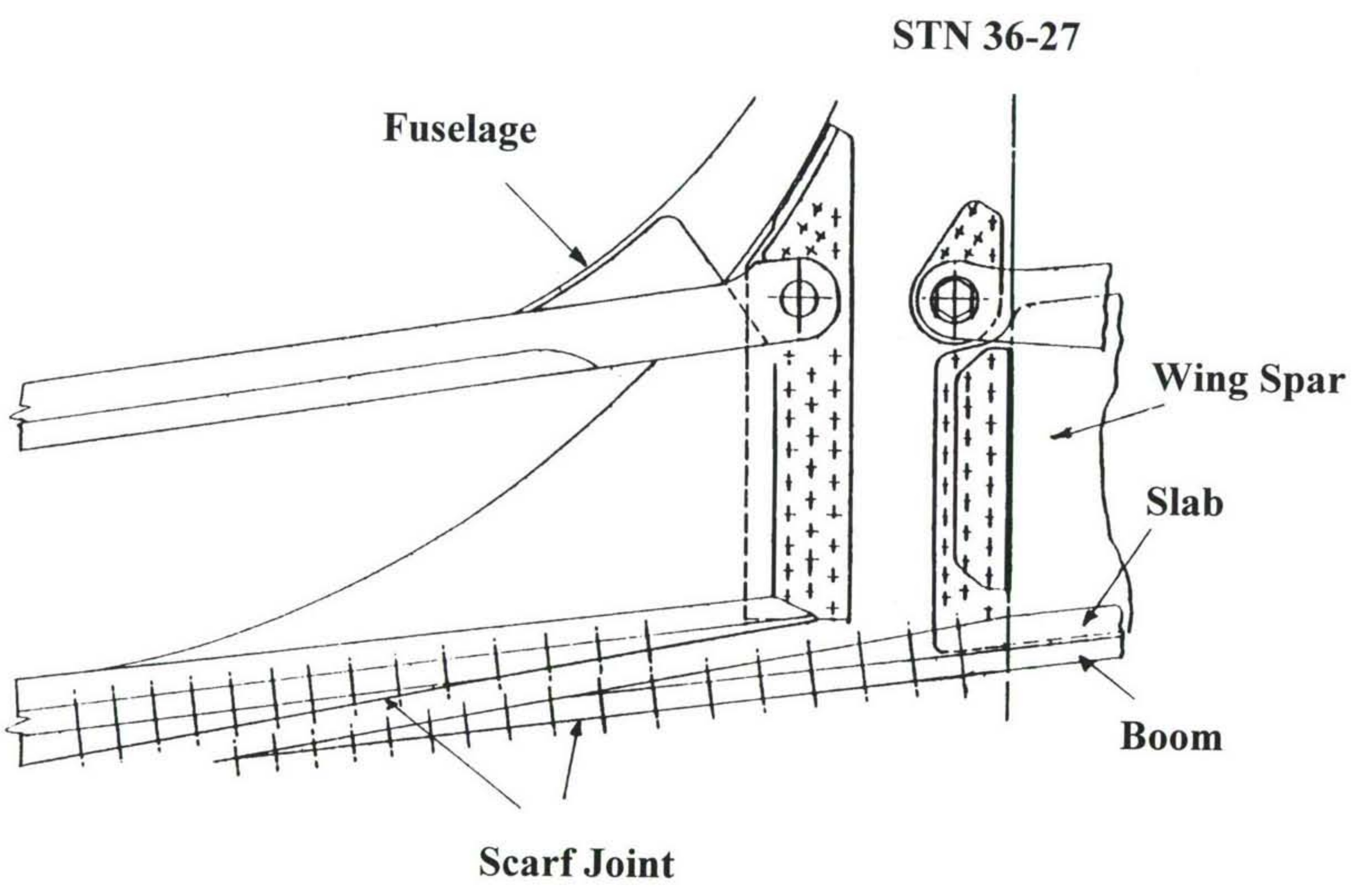

Figure 4 - Jetstream 31 Wing-Fuselage Joint

SERVICE BULLETIN EXPERIENCE RATING SYSTEM

ACCESS RATING

0 -	DAMAGE CAN BE DETECTED DURING WALKAROUND INSPECTION (OBVIOUS DAMAGE)
1 -	DAMAGE CAN BE DETECTED DURING LIGHT MAINTENANCE INSPECTION - MINIMUM ACCESS
2 -	DAMAGE CAN BE DETECTED DURING MODERATE INSPECTION - MODERATE ACCESS
3 -	DAMAGE CAN BE DETECTED DURING HEAVY MAINTENANCE INSPECTION - HEAVY ACCESS

FREQUENCY OF DEFECTS NOTED RATING (% OF AFFECTED UNMODIFIED AIRPLANES BEYOND THE S/B THRESHOLD ON WHICH DEFECTS HAVE BEEN FOUND)

0 -	FEW DEFECTS NOTED (LESS THAN 10%)
2 -	DEFECTS NOTED BUT NOT SIGNIFICANT AMOUNT (10-25 %)
4 -	SUBSTANTIAL AMOUNT OF DEFECTS NOTED (MORE THEN 25 %)

SEVERITY RATING

0 -	AIRWORTHINESS NOT AFFECTED. AIRPLANE CAN FLY WITH DAMAGE.
2 -	DAMAGE NOT OF IMMEDIATE CONCERN, BUT COULD PROGRESS OR SECONDARY DAMAGE
4 -	DAMAGE REQUIRES IMMEDIATE RESPONSE, AIRWORTHINESS AFFECTED

INSPECTABILITY RATING

0 -	HIGH PROBABILITY OF DETECTING DAMAGE (LOW PROBABILITY OF MISSING DAMAGE)
2 -	REASONABLE OR MODERATE PROBABILITY OF DETECTING DAMAGE (SOME PROBABILITY OF MISSING DAMAGE)
4 -	LOW PROBABILITY OF DETECTING DAMAGE (SIGNIFICANT PROBABILITY OF MISSING DAMAGE)

ADJACENT STRUCTURE DAMAGE RATING (MSD, CORROSION, ETC.)

0 -	LOW PROBABILITY OF ADJACENT STRUCTURE DAMAGE
1 -	...
2 -	...
3 -	HIGH PROBABILITY OF ADJACENT STRUCTURE DAMAGE

Figure 5 - Service Bulletin Experience Rating System

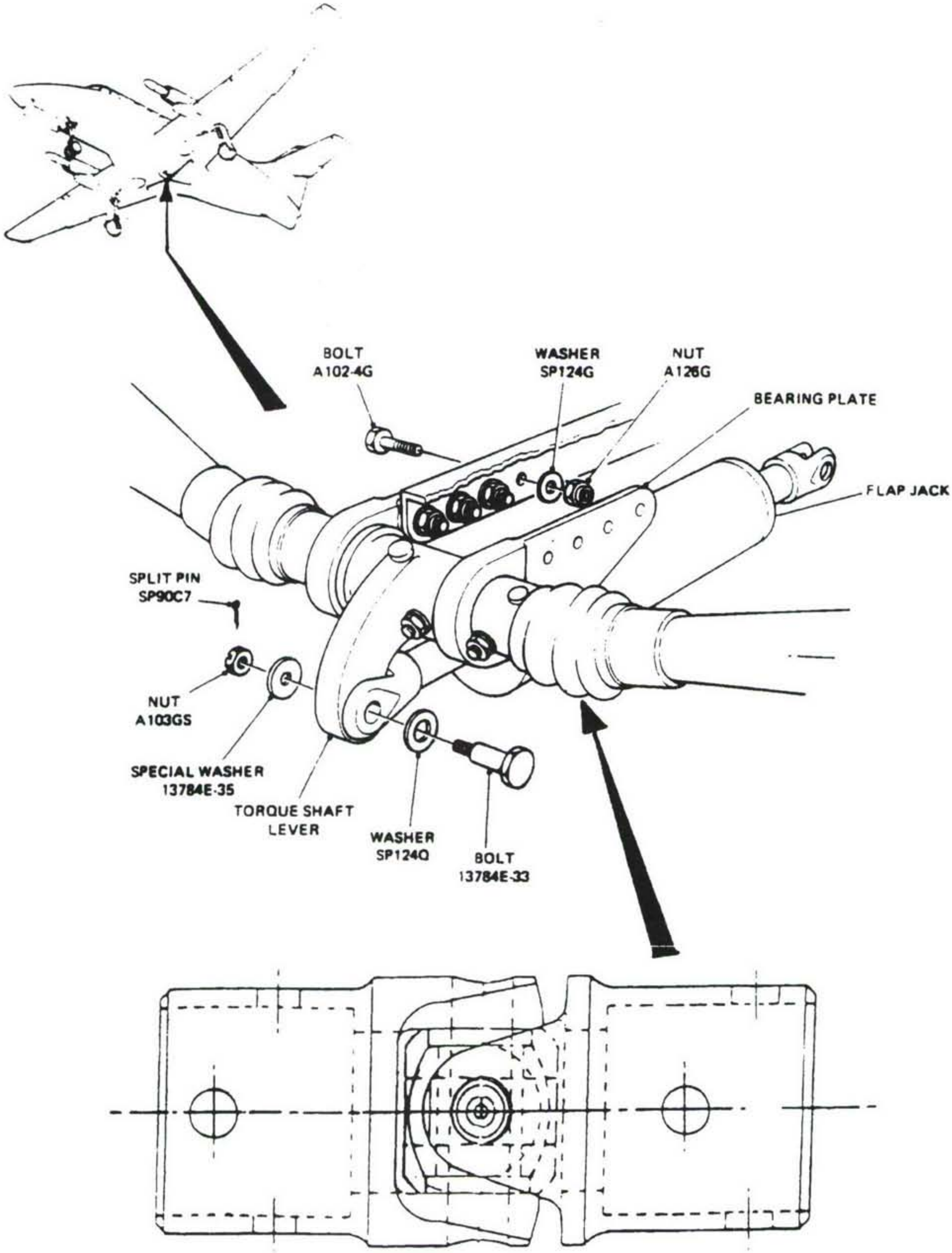

Figure 6 - Jetstream 31 Flap Universal Joint

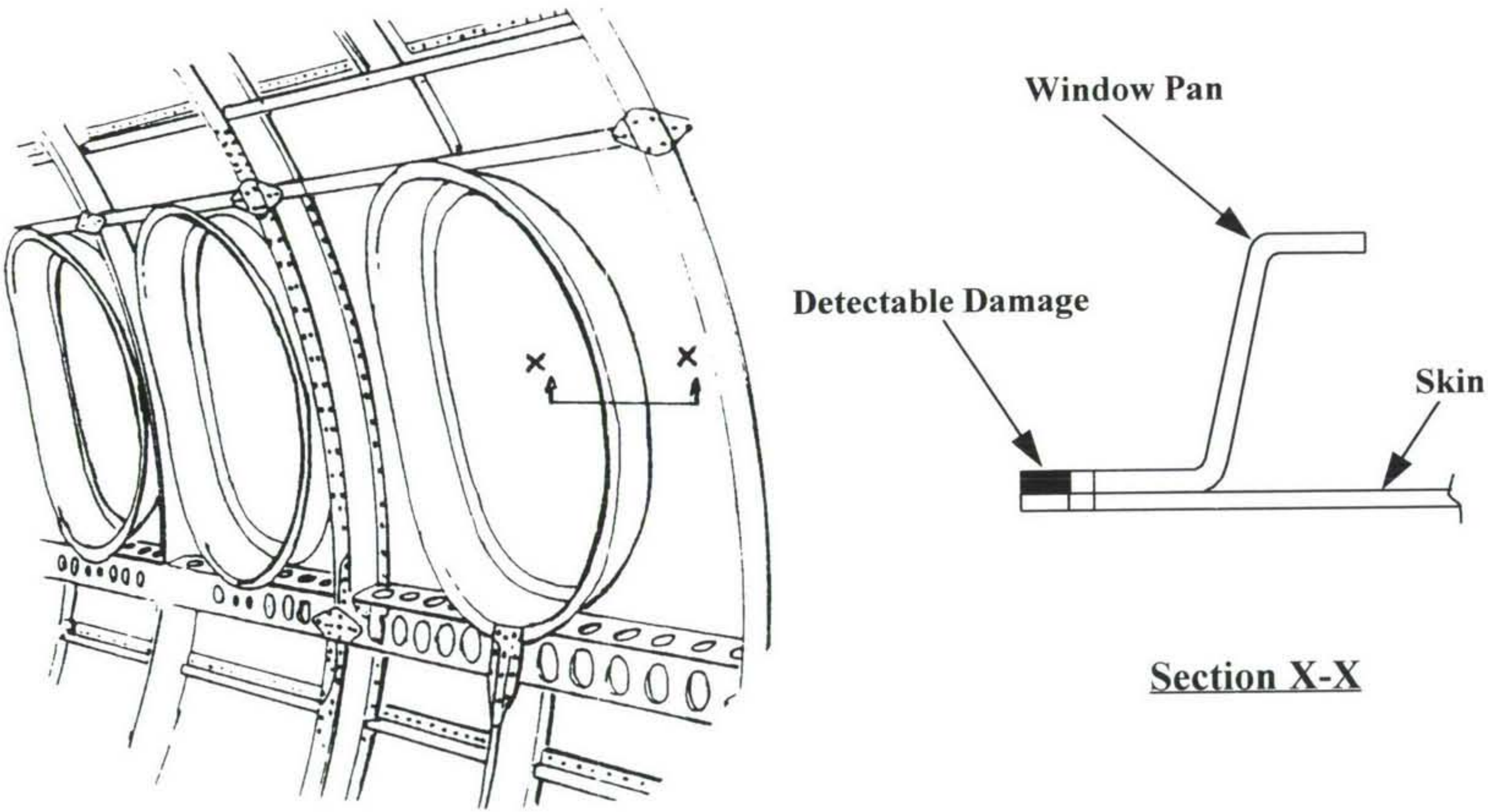

Figure 7 - Jetstream 31 Cabin Window Surround

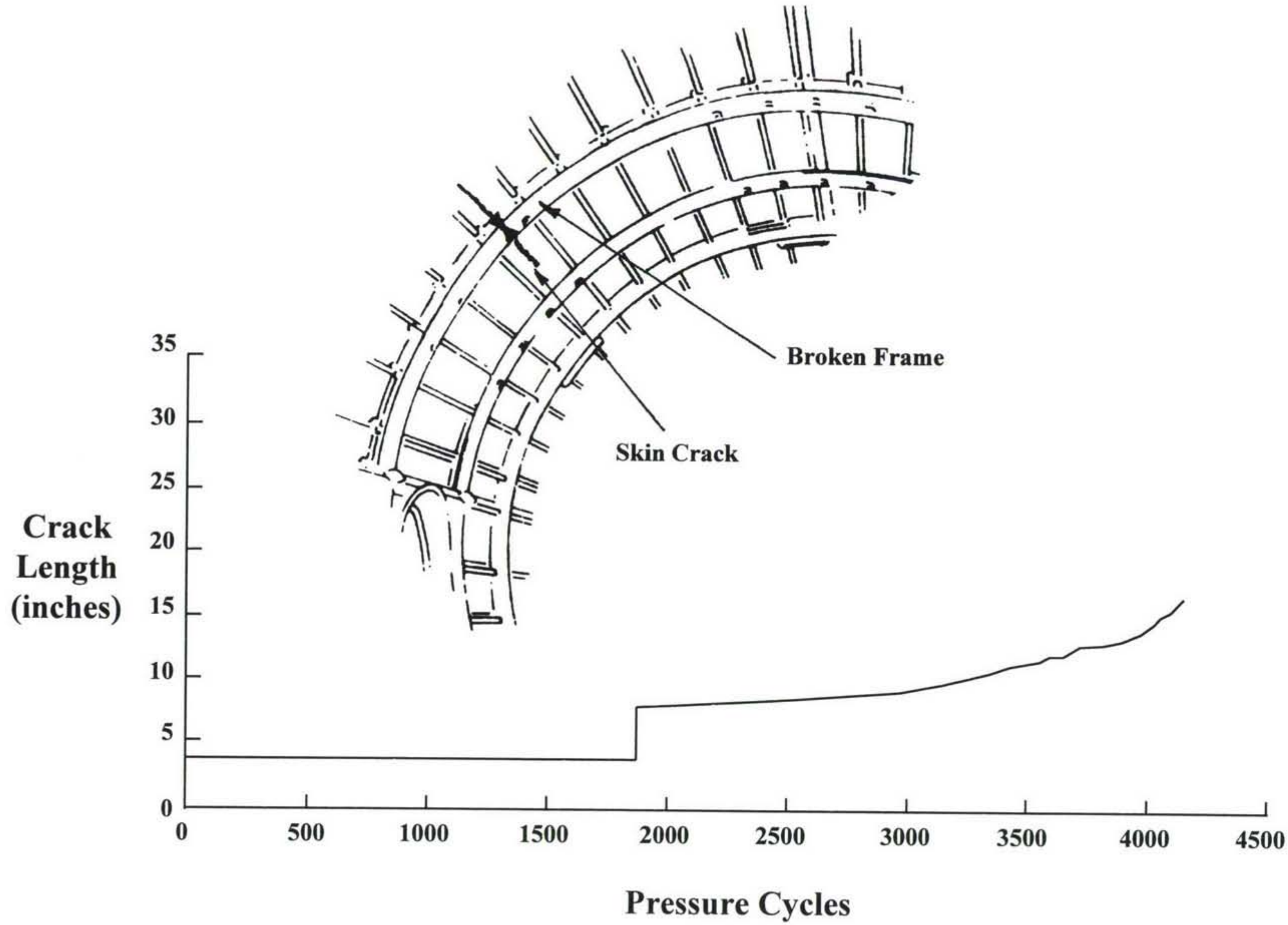

Figure 8 - Crack Growth in Fuselage Skin Panel

REFER TO DRG 141R0424 FOR WEIGHT AND BALANCE CHANGES

DAMAGE REPORTED AT .... FLYING HRS. .... LANDINGS	THIS DRAWING HAS BEEN GIVEN INITIAL CLEARANCE FOR INTRODUCTION ONTO THE AIRCRAFT (VALID FOR 12 MONTHS) SIGNED - .... NAME - .... DATE -	THIS DRAWING HAS BEEN GIVEN FINAL CLEARANCE FOR INTRODUCTION ONTO THE AIRCRAFT SIGNED - .... NAME - .... DATE - ....
DO NOT SCALE		

ISSUE No.			THE TECHNICAL CONTENT OF THIS REPAIR SCHEME/INFORMATION HAS BEEN APPROVED UNDER THE AUTHORITY OF UK CAA APPROVAL No. DAI/9386/92	SHT.	ISS.
DATE				DRG. STATUS	
PREPARED					
TITLE -				SHT. OF	

Figure 9 - Revised Sign-Off Box for Repair Drawings

*U.S. Government Printing Office: 1996 - 704-982